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This report discusses a field demonstration of a methodology for characterizing an aquifer's geohydrology in the detail required to design an optimum network of wells and/or infiltration galleries for bioreclamation systems. The project work was conducted on a 1-hectare test site at Columbus AFB MS. The technical report is divided into two volumes. Volume I describes the test site and the well network, the assumptions, and the application of equations that define groundwater flow to a well, the results of three large-scale aquifer tests, and the results of 160 single-well pump tests. Volume II describes the bore hole flowmeter tests, the tracer tests, the geological investigations, the geostatistical analysis and the guidelines for using groundwater models to design bioreclamation systems.

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EXECUTIVE SUMMARY

In order to successfully provide aquifer remediation, bioreclamation systems need to deliver the proper nutrient concentrations to the areas of contamination. The project's primary objective was to develop and to demonstrate a methodology for characterizing an aquifer's geohydrology in the detail required to design an optimum network of wells and/or infiltration galleries for bioreclamation systems. The project work included performing and analyzing a series of aquifer tests and recirculating tracer tests on a 1-hectare test site located at Columbus Air Force Base, Mississippi. The tests' results demonstrate that bioreclamation systems can not be adequately designed without first characterizating the spatial variability in the hydraulic conductivity field. The recommended methodology includes multiwell aquifer tests and geological investigations and focuses on borehole flowmeter tests to measure the vertical variation in the horizontal hydraulic conductivity values at each well location.

A borehole flowmeter test involves measuring the incremental discharges along the fully screened wells during small-scale pumping/injecting tests. Within the well, vertical zones having high horizontal flow rates indicate zones of high horizontal hydraulic conductivity, and vice versa. The method is quick and simple to implement. At many well locations, the horizontal hydraulic conductivity values measured at 0.3-meter vertical intervals varied over a 3 to 5 order of magnitude range. At some of the well locations, the variation in the hydraulic conductivity field caused approximately 70 percent of the groundwater flow to occur within less than 10 percent of the aquifer thickness.

The accuracy of the borehole flowmeter results were compared with the results of fourteen small-scale tracer tests and one large-scale tracer test. The fourteen small-scale tracer tests were uniformly distributed over a 3,000 m^2 area. These tracer tests typically had distances of 4 to 7 meters between the injection and the withdrawal wells. The one

large-scale tracer test included four withdrawal wells and one injection well and covered the entire 3,000 m^2 area. Given the uncertainty associated with interpolating among the hydraulic conductivity values at the wells used during the tracer tests, good agreement was shown between the hydraulic conductivity values calculated from the tracer breakthrough curves and the borehole flowmeter tests.

The statistical and structural properties of the hydraulic conductivity field at the test site indicate that the aquifer is heterogeneous. A measure of heterogeneity is the variance of the natural logarithm of the hydraulic conductivity measurements, lnK. At the test site lnK is 4.7. The estimates of lnK for an aquifer composed of coastal sands in Cape Cod, Massachusetts, studied by the United States Geological Survey and for an aquifer composed of glacial till in Borden, Canada, studied by Stanford and Waterloo Universities, are less than 0.5. The demonstration of the site characterization methodology in a very heterogeneous aquifer insures that the procedures should be valid for a variety of aquifer types ranging from uniform sands to a complex mixture of gravel, sand, and clay.

In order to demonstrate and document the effectiveness of the site characterization methodology, two reports were written. Volume I describes the test site and the well network, the assumptions and the application of equations that define groundwater flow to a well, the results of three large-scale aquifer tests, and the results of 160 single-well pump tests. Volume II describes the borehole flowmeter tests, the tracer tests, the geological investigations, the geostatistical analyses, and the guidelines for using groundwater models to design bioreclamation systems.

SUMMARY OF THE SITE CHARACTERIZATION METHODOLOGY

The flowchart and Tables 1 and 2 describe the major tasks that comprise the site characterization methodology. The site characterization methodology includes designing a well network, preparing a preliminary assessment of the site's heterogeneity, measuring the

vertical variation in the horizontal hydraulic conductivity, and collecting calibration data for groundwater flow models. Deviations from the flowchart can be expected to result from having prior information of the geohydrological conditions, an existing well network, and/or concerns related to the geochemistry or microbiology. The detailed documentation concerning the site methodology development provides information from which alternative approaches can be prepared. An objective of the site characterization is to characterize the aquifer heterogeneity. If the aquifer is very heterogeneous, two problems may arise.

The first problem related to heterogeneity occurs when the vertical profiles of horizontal hydraulic conductivity at the well locations are very different. In these instances, no validated procedures exist for the proper interpolation among the profiles. As a result, the representativeness of the interpolated three-dimensional hydraulic conductivity field is unknown. This uncertainty becomes embedded into the groundwater modeling results and leads to uncertainty in the evaluation of the hydraulic design of the bioreclamation system. The second problem related to heterogeneity occurs where the variations among the hydraulic conductivity of the aquifer materials are very large. There it may be too costly to install a system of wells and/or infiltration galleries to deliver an adequate flow rate to less permeable target zones of the aquifer material.

FLOWCHART OF THE MAJOR TASKS IN THE SITE CHARACTERIZATION METHODOLOGY

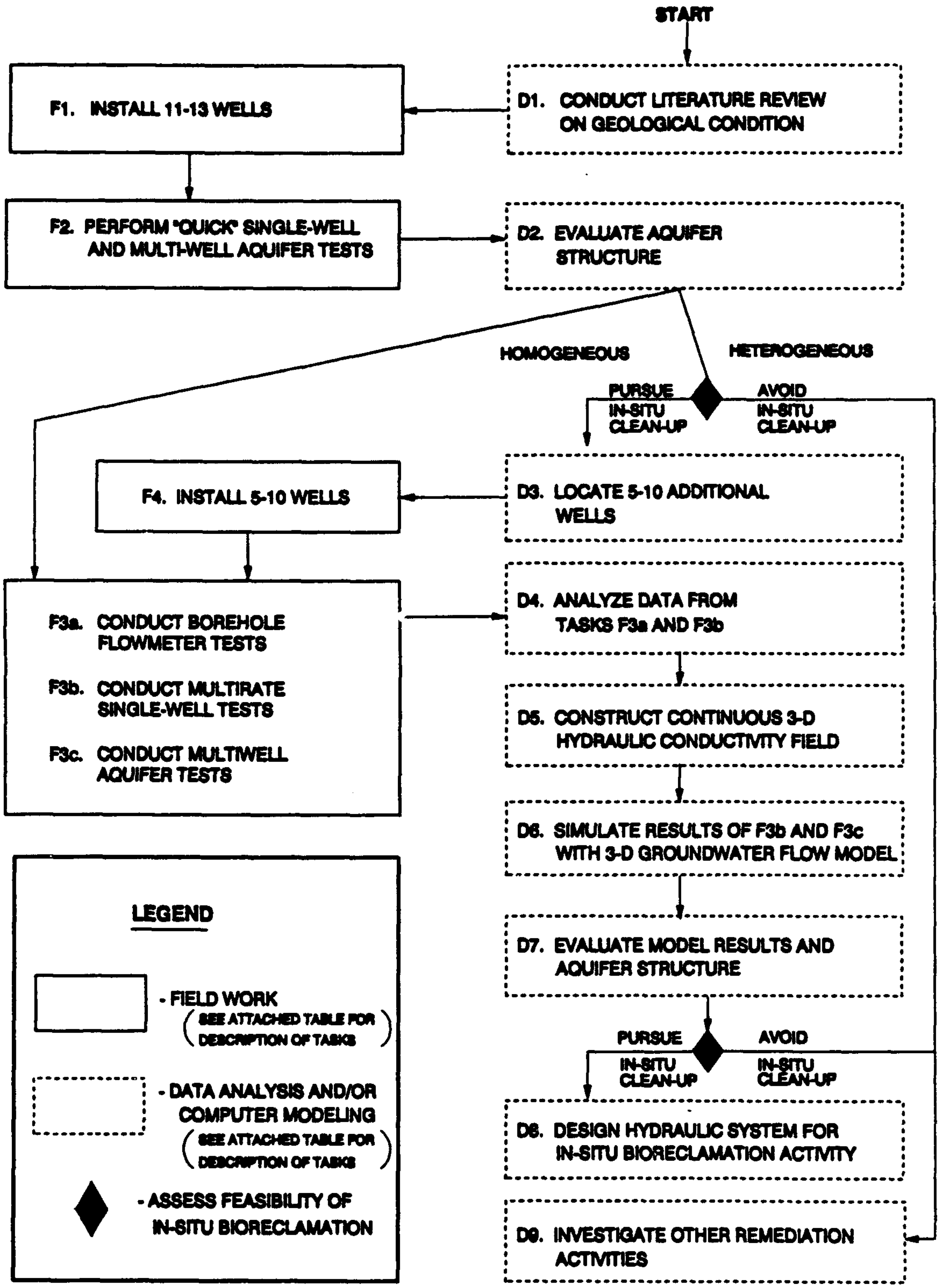

TABLE 1. DESCRIPTION OF THE TASKS ASSOCIATED WITH FIELDWORK

	Task	Description
F1.	Install 11-13 wells	Use a Hollow-Stem Auger to install 11 to 13 fully screened wells. Nine of these wells should be placed on a regular grid; the remaining wells should be placed 2 to 4 meters from a well near the interior of the well network. (Volume I, Section II)
F2.	Perform "Quick" Single-Well and Multiwell Aquifer Tests	Conduct 10- to 40-minute moderate to low flow single-well tests at each well to determine the transmissivity pattern. Slug-tests should not be conducted because they are strongly affected by the disturbed zone around the wells. During the single-well tests monitor the drawdown in any close wells to determine values for storage coefficients and hydraulic conductivity. Note whether large vertical variations of hydraulic conductivity exist. (Volume I, Sections V, VI, VII, and VIII)
F3a.	Conduct Borehole Flowmeter Tests	While pumping/injecting at a low rate, perform borehole flowmeter tests to determine transmissivity and three-dimensional hydraulic conductivity patterns. Conduct a separate borehole flowmeter test at high injection rates if large portions of the unsaturated zone need to be characterized. Each test should last 40 to 90 minutes. (Volume II, Section III)
F3b.	Conduct Multirate Single-Well Tests	Conduct the necessary single-well tests to determine how sensitive the calculated transmissivity value is to the pumping rate. Results from the borehole flowmeter tests may be acceptable for inclusion in the data base. If the aquifer is rather homogeneous only several of these tests are needed. (Volume I, Sections VII and VIII)
F3c.	Conduct Multiwell Aquifer Tests	During Tasks F3a and F3b, monitor the drawdown in nearby wells. (Volume I, Sections V and VI)

TABLE 2. DESCRIPTION OF TASKS ASSOCIATED WITH DATA ANALYSIS AND/OR COMPUTER MODELING

	Task	Description
D1.	Conduct Literature Review on Geological Conditions	Obtain information on the type of depositional environments responsible for the aquifer material. Extract any information about the structure of the hydraulic conductivity field. (Volume II, Section IV)
D2.	Evaluate Aquifer Structure	Determine whether bioreclamation appears to be a viable remediation approach, given the known trends in the hydraulic conductivity field. (Volume I, Sections VI and VIII, and Volume II, Section III)
D3.	Install 5-10 Additional Wells	Install wells in areas where the greatest differences occur in the transmissivity field and/or where improvements can be made in the variogram calculations. Use program similar to WELPLAN. (Volume I, Section II)
D4.	Analyze Data from Tasks F3a and F3b	Determine vertical variations of hydraulic conductivity at each well site. Determine whether calculated transmissivities are sensitive to pumping rate. (Volume I, Sections V, VI, VII, and VIII, and Volume II, Section III)
D5.	Construct Continuous 3-D Hydraulic Conductivity Field	From three-dimensional hydraulic conductivity data, construct a continuous three-dimensional grid. The method for doing this is beyond scope of this report. (Volume II, Sections VI and VII, discusses some options)
D6.	Simulate Results of F3b and F3c with Three-Dimensional Groundwater Flow Model	If the aquifer is heterogeneous, transmissivities and storage coefficients will be sensitive to the pumping rates, test duration, and orientation/distance between the pumped and the observation well. The appropriateness of a groundwater flow model's accuracy is to reproduce the drawdowns observed during Tasks F3a and F3b (Volume I, Section VI, and Volume II, Section VIII)
D7.	Evaluate Model Results and Aquifer Structure	Based on the comparison between the predicted and the observed well responses determine whether to pursue in-situ bioreclamation.

TABLE 2. DESCRIPTION OF TASKS ASSOCIATED WITH DATA ANALYSIS AND/OR COMPUTER MODELING (CONCLUDED)

Task	Description
D8. Design Hydraulic System for In-Situ Bioreclamation	Use groundwater model to evaluate alternative designs for bioreclamation systems. (Volume II, Section VIII discusses some approaches)

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PREFACE

This report was prepared by the Tennessee Valley Authority, Engineering Laboratory, 129 Pine Road, Norris, Tennessee 37828 under Military Interdepartmental Purchase Request (MIPR) N88-28 for the Air Force Engineering and Services Center (HQ AFESC/RD), Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, 32403-5323.

The report discusses a field demonstration of a methodology for characterizing an aquifer's geohydrology in the detail required to design an optimum network of wells and/or infiltration galleries for bioreclamation systems. The project work was conducted on a 1-hectare test site located at Columbus AFB, Mississippi. The field work occurred between August 1987 and September 1989.

The technical report is divided into two volumes. Volume I describes the test site and the well network, the assumptions, and the application of equations that define groundwater flow to a well, the results of three large-scale aquifer tests, and the results of 160 single-well pump tests. Volume II describes the bore hole flowmeter tests, the tracer tests, the geological investigations, the geostatistical analyses, and the guidelines for using groundwater models to design bioreclamation systems.

The report discusses a methodology that includes field procedures and data analysis methods advocated by the Tennessee Valley Authority. The publication of the report by the Air Force does not constitute an endorsement of the methodology by the Air Force.

This technical report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

z = depth (L)

Δz_i = the thickness of layer i

h = hydraulic head (L)

h_R = hydraulic head in the aquifer prior to pumping (L)

$h(r,t)$ = hydraulic head in the aquifer at radius r and time t (L)

H = total aquifer thickness (L)

K = aquifer hydraulic conductivity (L/T)

K_i = hydraulic conductivity for layer i

K_s = hydraulic conductivity of skin effect

K_c = calculated hydraulic conductivity for aquifer

$T = \int_H K\,dz = \bar{K}H$ = transmissivity (L^2/T)

$S = \int_H S_o\,dz + S_y = S_oH + S_y$ = storage coefficient (-)

S_i = storage coefficient for layer i

S_y = drainable porosity = specific yield (-)

S_o = specific storage coefficient (-)

D = diffusivity = T/s (L^2/T)

r = radial distance from the center of the well (L)

R [radius of influence] = $\sqrt{\dfrac{2.25Tt}{S}}$

r_w = radius of well (L)

r_s = radius of skin effect (L)

t = elapsed time (T)

t_o = time intercept on a semilogarithmic plot where drawdown equals zero (T)

Q = discharge rate (L^3/T)

ΔQ_i = the flow to (or from) layer i

$W(u)$ [well function] = $\ln\left(\dfrac{1}{1.781\cdot u}\right) \quad \sum_{n=1}^{\infty} \quad (-u)^n \quad \dfrac{1}{n\cdot n!}$

u [dimensionless time] = $\dfrac{r^2S}{4\,Tt}$

s = drawdown in the aquifer after pumping (L)

Δs_i = drawdown for layer i

s' = drawdown adjusted by the Jacob correction factor (L)

B = aquifer thickness (L)

c [Theis correction factor] = $Q/2\pi Kb^2$ (-)

LIST OF SYMBOLS (CONCLUDED)

θ = angular direction (-)

V_d = the cumulative volume of water discharged from a well during an aquifer test

V_i = the volume of contained in when the cone-of-depression is integrated

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SECTION I

INTRODUCTION

A. OBJECTIVE

The goal of this project is to develop and demonstrate a methodology for characterizing an aquifer's geohydrology. Site characterization is to be sufficient for designing a system of wells and/or infiltration galleries that optimize the transport of nutrients to targeted zones during in-situ bioreclamation activities. The methodology includes the procedures required to: (1) properly design and install a groundwater well network for site characterization activities; and (2) properly design, conduct, and analyze aquifer well tests to measure hydraulic conductivities in three dimensions. Numerous field tests' results from Columbus Air Force Base (CAFB), Mississippi, demonstrate that three-dimensional characterization data is a prerequisite to accurate prediction of advective transport in heterogeneous aquifers. The methodology also provides guidelines on how to apply groundwater transport models to design an effective network of wells and/or infiltration galleries for bioreclamation activities.

B. BACKGROUND

An alternative to waste extraction and conventional pumping and treatment methods at hazardous waste and spill sites is to treat the wastes in-situ. In-situ biodegradation, commonly referred to as bioreclamation, is based on the concept of stimulating bacteria to metabolize the contaminants. Over the last 25 years, degradation of organics has been extensively studied and become well understood in the laboratory. In general, the application of bioreclamation technology to full-scale field experiments has not met with the success that laboratory data would suggest. One problem associated with designing and operating in-situ bioreclamation is characterizing the properties of the aquifer that determine advective transport of the injected nutrient solution.

In an aquifer, the three-dimensional structure of the hydraulic conductivity field will control the groundwater flow patterns. The rate

at which the nutrient solution is advected will be controlled by the hydraulic conductivity of the different aquifer materials. The rate at which the nutrient solution spreads/disperses will be controlled by the interconnectiveness among the different hydraulic conductivity zones. Thus, proper characterization of the spatial variability in the hydraulic conductivity field is a prerequisite to accurate groundwater transport predictions needed to evaluate the effectiveness of different withdrawal pumping schemes for bioreclamation and pump-and-treat activities.

To properly characterize an aquifer's hydraulic properties requires an effective method for measuring the spatial variability in the hydraulic conductivity field. Recently, the Tennessee Valley Authority (TVA) and the Massachusetts Institute of Technology (MIT) demonstrated that a borehole flowmeter can be used during a single-well pumping test to measure the discharge rate from any specified vertical interval within a fully screened well (Rehfeldt, et al., 1990). The methodology developed by TVA uses a borehole flowmeter to calculate hydraulic conductivities in three dimensions. Overall, the methodology includes significant advancements in the design, construction, and use of borehole flowmeters and in the design, implementation, and data analysis of multiwell and single-well aquifer tests.

C. SCOPE

1. Description of Tasks

The project centered on conducting and analyzing a series of pump and tracer tests at an uncontaminated area of the terrace aquifer at the CAFB. The test site is situated on the youngest terrace in a series of Pleistocene and Holocene Age deposits that are associated with the Tombigbee and Buttahatchee Rivers. The sand, gravel, silt, and clay deposits occur in irregular lenses and layers.

The test site covers 1 hectare and has 37 fully screened groundwater wells. Well locations were based on several considerations including: (1) characterizing statistical properties of the hydraulic conductivity field; and (2) conducting small (1-5 meters) and large (5-50

meters) pump and tracer tests. Site characterization activities included multiwell aquifer tests, single-well pumping and injection tests, and two sets of borehole flowmeter measurements. The site characterization results and methodology were validated by comparison with the results from a series of small-scale and one large-scale tracer tests. A summary of the project activities is listed in Tables 3 and 4.

TABLE 3. SUMMARY OF PROJECT ACTIVITIES: SITE CHARACTERIZATION PROJECTS

	Project	Result
1.	5-Day Large-Scale Aquifer Tests With a Constant 68 L/min Discharge Rate	T at 27 wells, S at 9 wells
2.	5-Day Pulsing Large-Scale Aquifer Tests With an Average Pumping Rate of 68 L/min	T at 27 wells, S at 27 wells
3.	8-Day Large-Scale Aquifer Tests With a Constant 110 L/min Discharge Rate	T at 27 wells, S at 12 wells
4.	Seven Small-Scale Aquifer Tests (1 hour to 3 hours) With Pumping Rates From 34 to 81 L/min	T at 35 wells, S at 35 wells
5.	34-Liter Slug Tests	T at 37 wells
6.	2-Minute 34 L/min Pumping Tests	T at 37 wells
7.	Single-Well Injection Tests at 22 L/min	T at 37 wells
8.	One Hundred Forty-Nine Multiple Rate (6 L/min to 80 L/min) 115 Pumping Tests at the Same Well	149 values of T at 37 wells (an average of about 3 tests per well)
9.	Borehole Flowmeter Measurements During 22 L/min Injection Tests	881 K_g at 37 wells
10.	Borehole Flowmeter Measurements During 30 L/min Withdrawal	362 K_g at 21 wells
11.	Borehole Flowmeter Measurements During 15 L/min Withdrawal	380 K_g at 21 wells

Notes: (1) T = transmissivity
S = storage coefficient
K = hydraulic conductivity
(2) Drawdown data sets consisted of manual and/or automatic measurements made by a data logging system connected to a

TABLE 3. SUMMARY OF PROJECT ACTIVITIES: SITE CHARACTERIZATION PROJECTS (CONCLUDED)

pressure transducer. Storage coefficients were calculated only for the data from the pressure transducers.

(3) Each hydraulic conductivity measurement is based on the average discharge across a 0.3 meter vertical section of a well screen. The number of measurements taken at each well averages about 21 but will vary because of the different thicknesses of the saturated zone during pumping at each well.

TABLE 4. SUMMARY OF PROJECT ACTIVITIES: TRACER TESTS

Tracer Test	
1. 8-hour five-spot tracer test for wells spaced 3.6 to 4.6 meters apart with a 31 L/min injection rate	Breakthrough curves at 4 wells
2. 25-hour five-spot tracer test for wells spaced 3.6 to 6.3 meters apart with a 38 L/min injection rate	Breakthrough curves at 4 wells
3. Three 36-hour doublet tracer tests conducted at 3 well pairs with spacings of 5.2, 6.7, and 6.2 meters with injection rates between 11.5 and 14.2 L/min	Breakthrough curves at 3 wells
4. Four 70-hour doublet tracer tests conducted at 4 well pairs with spacings of 7.3, 8.9, 15.2, and 15.8 meters with injection rates between 15.1 and 34.1 L/min	Breakthrough curves at 4 wells
5. One 168-hour five-spot tracer test with injection and pumping wells 31 meters apart and with 27 monitoring wells at distances from 4.8 to 31.1 meters from the injection well with an injection rate of 106 L/min	Breakthrough curves at 27 wells

2. Description of the Report

The project results are contained in two volumes. Volume I describes the test site, the data and results for the multiwell aquifer tests, and the data and results for the single-well hydraulic tests. Volume II contains the results for the borehole flowmeter measurements,

the tracer tests, the geological investigations, and recommendations for applying groundwater models to effectively design a network of wells and/or infiltration galleries for bioreclamation activities.

Volume I includes nine major sections. Section I is the introduction. Section II describes the site location, the methods used to design the well network, and the methods used to install and develop the wells. Sections III and IV give a summary of the most relevant well equations and the limitations associated with their applications to heterogeneous aquifers. Sections V and VI provide the data and analysis of the multiwell aquifer tests. Sections VII and VIII provide the data and analysis of the single-well hydraulic tests. Section IX summarizes the important results in Section I to Section VIII.

Volume II includes seven major sections. Section I is the Introduction. Section II describes the development and application of the borehole flowmeter technique for measuring hydraulic conductivities in three dimensions. Sections III and IV describe the tracer tests and evaluate the accuracy of the borehole flowmeter results with respect to the tracer tests' results. Section V provides explanations for the complexity of the site and trends in the hydraulic conductivity data based on geological investigations. Section VI outlines the problems associated with applying interpolation schemes to point measurements of hydraulic conductivity. Section VII summarizes the important aspects of this methodology for characterizing the three-dimensional hydraulic conductivity field of any unconsolidated aquifer. Section VIII provides guidelines and recommendations on how to apply groundwater transport models to design an effective network of wells and/or infiltration galleries for any pump-and-treat bioreclamation scheme.

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SECTION II

TEST SITE AND WELL NETWORK

A. GENERAL SITE DESCRIPTION

1. TVA Macrodispersion Experiment (MADE) Site

The test site occupies approximately 1 of 25 hectares in the northeastern corner of CAFB that TVA is leasing from the U.S. Air Force for its MADE project. Since 1982, TVA has been conducting the MADE project for the Electric Power Research Institute. The MADE project centers on field experiments related to dispersion in saturated heterogeneous aquifers and consists of two types of field studies (Betson, et al., 1985). One study involves the monitoring of a relatively large-scale (100 meters) natural-gradient tracer experiment. The other study involves the detailed characterization of an aquifer's geohydrology.

Groundwater levels have been monitored across the MADE site since December 1984 using a network of both single and multistaged observation wells. Seasonal water table fluctuations range from 2 to 3 meters. The magnitude of the horizontal hydraulic gradient changes from approximately 0.2 percent, when the water table is low, to 0.5 percent when the water table is high. Vertical hydraulic gradients several orders of magnitude higher than horizontal hydraulic gradients exist over most of the site. These vertical gradients can be attributed to the complex flow patterns produced by the heterogeneities in the hydraulic conductivity field.

The MADE project test site is approximately 6 km east of the Tombigbee River and 2.5 km south of the Buttahatchee River, and lies above the 100-year flood plain of both rivers. According to Russell (personal communications, 1982), the site is situated on the youngest terrace deposits associated with the Buttahatchee River. The aquifer is composed of approximately 11 meters of terrace deposits that primarily consist of poorly-sorted to well-sorted, sandy gravel and gravelly sand that often occur in irregular lenses and layers. The terrace deposits are unconformably underlain by the Cretaceous Age Eutaw Formation consisting of marine clay, silt, and sand (Kaye, 1955).

Visual inspection of the facies exposed at a quarry located a few kilometers from the site show a complex series of lenses that have significantly different physical and hydrological properties. Rehfeldt, et al. (1989), map the facies and show that the facies are lenticular with the ratio of length to thickness ranging from nearly 1 for small lenses to more than 20. At the quarry, the thickness of the lenses varied from 1 millimeter to 1 meter. Detailed measurements of hydraulic conductivity at the MADE site by Boggs, et al. (1990), show that order of magnitude changes in the hydraulic conductivity values occur over vertical distances as small as 0.15 meter. This type of spatial variability is consistent with the results of facies mapping and three-dimensional hydraulic conductivity measurements presented in Volume II.

At the MADE site, the land surface slopes gently northward from elevation 66.5 meters MSL in the southeastern corner to 64.6 meters MSL at the northern extreme. Rainfall at CAFB averages 144 cm annually, and is fairly uniform in distribution throughout the year. Most precipitation occurs during winter and early spring, with the driest seasons being summer and early fall. The climate is temperate with a mean annual air temperature of 17°C. The mean maximum daily temperature in July is 33°C, and the mean minimum daily temperature in January is 3°C (USAF, 1982).

2. Site Location

In July 1988, single-well pump tests were conducted at the five reconnaissance wells shown in Figure 1. Based on the results in Table 5, the test site was located in the northeast section of the MADE test area (Figure 1). The test site is centered on reconnaissance Well R05 because of its relatively high average hydraulic conductivity.

TABLE 5. RESULTS OF PUMP TESTS IN RECONNAISSANCE WELLS

Well	Number of Well Tests	Arithmetic Avg of K (cm/s)
R01	2	0.0010
R02	5	0.0005
R03	2	0.0045
R04	2	0.0070
R05	3	0.0200

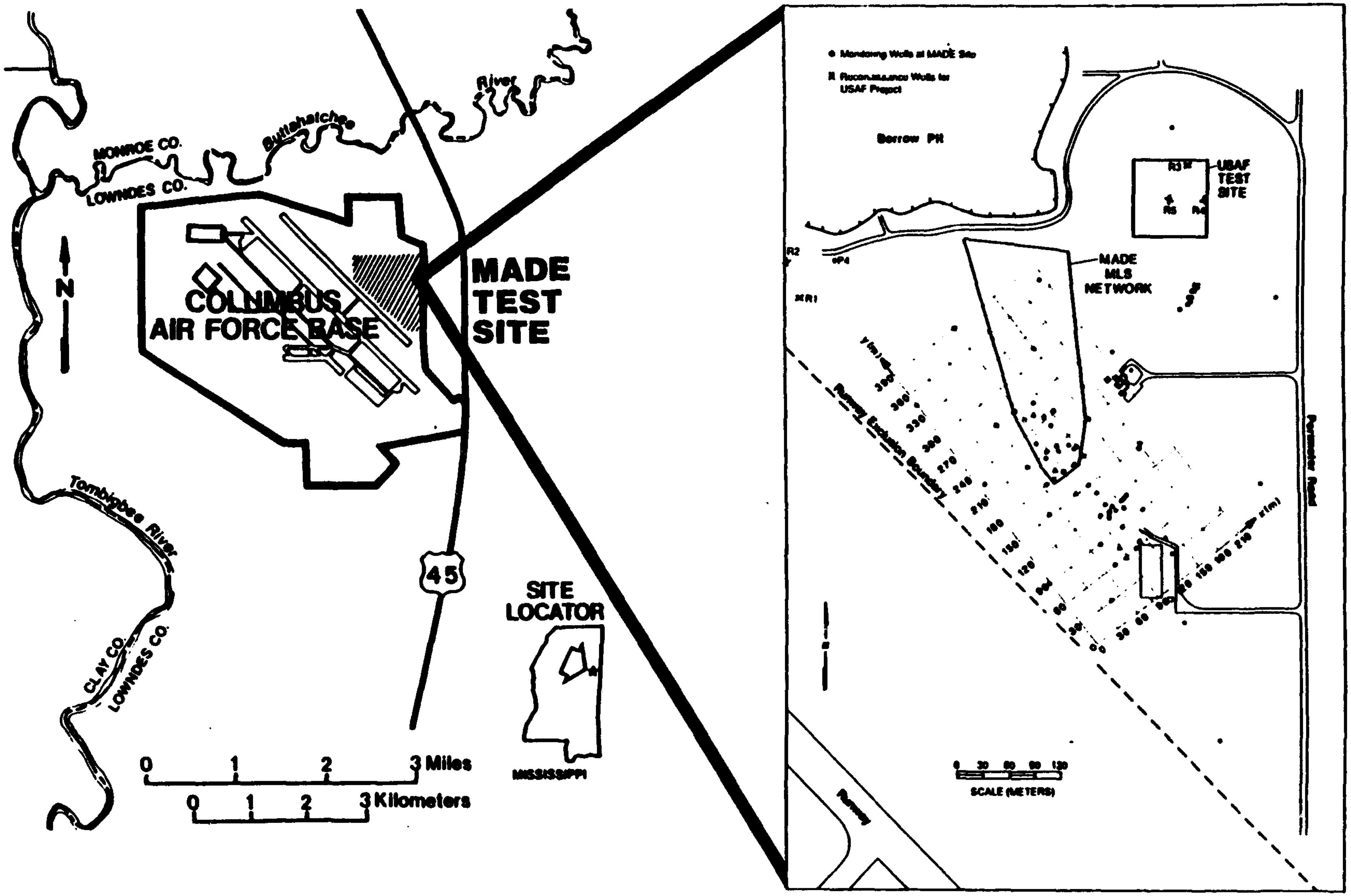


Figure 1. Location Map for Columbus AFB and the TVA Macrodispersion Experimental Site.

B. DESIGN OF THE WELL NETWORK

1. Geostatistics and Kriging

Because of the general popularity that geostatistics has had in the hydrosciences over the last 20 years (Delhomme, 1976), kriging was selected a priori as the method for interpolating the measured hydraulic conductivity field data. The theory of geostatistics was developed by G. Matheron (1965, 1971) to allow the drawing of statistical inferences, considering not only sample values but also implicit relationships in the geometry of the sample space.

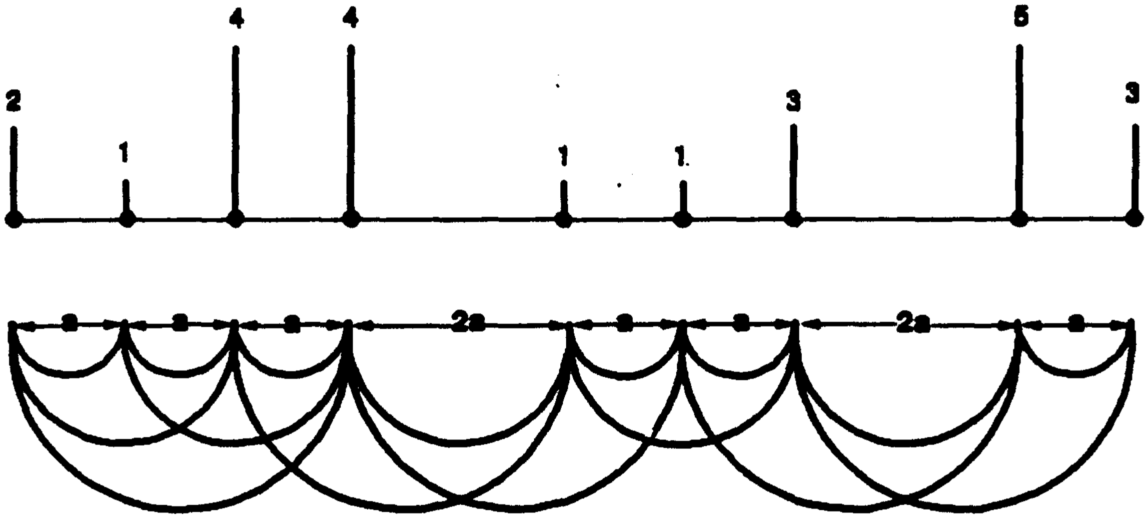
As an interpolation scheme, kriging has several advantages over alternative approaches such as least squares, polynomial interpolation, and distance weighing of data points. Kriging restitutes the measured values as estimates at the data points whereas the least squares method does not, since it is meant for regression rather than interpolation. Kriging will not produce the contortions that result from trying to force a polynomial to fit the data and makes a minimum of assumptions for the structure of the field. Last but not least, kriging also provides an assessment of the accuracy of the estimates (Kafritsas and Bras, 1981).

The theoretical development and application of kriging is beyond the scope of this report. For those interested, a detailed description of the kriging algorithms is found in Dowd (1985), Kafritsas and Bras (1981), Vomvoris (1982), and Olea (1975). The cornerstone of the kriging algorithms is the semivariogram, which is an intrinsic random function that describes the covariance structure of the data points. Equation (1) is a general expression for the variogram and Equation (2) is the form of the variogram for a one-dimensional data set measured at a unit lag. Figure 2 provides an example calculation for a one-dimensional data set.

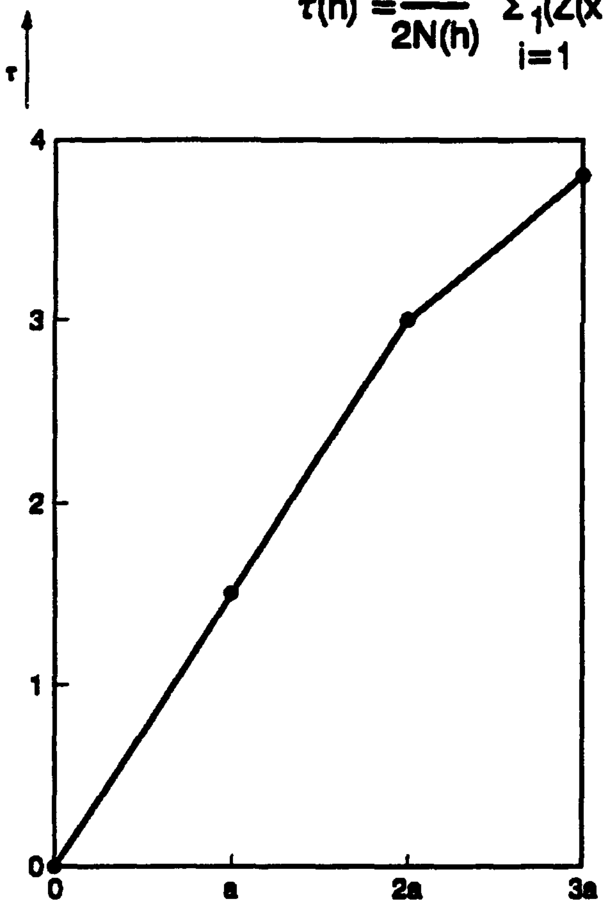
$$\tau(h) = 1/2 \text{ variance } (Z(x_i + h) - Z(x_i)) \tag{1}$$

$$\tau(h) = \frac{1}{2*N(h)} \sum_{i=1}^{N(h)} (Z(x_i + h) - Z(x_i))^2 \tag{2}$$

where: h = the lag distance between points (L)



$$\tau(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left(Z(x_i+h)-Z(x_i)\right)^2$$



EXAMPLE CALCULATION FOR h = a

i	$Z(x_i+h)$	$Z(x_i)$	$[Z(x_i+h)-Z(x_i)]^2$	τ(a)
1	1	2	1^2	1/2
2	4	1	3^2	10/4
3	4	4	0^2	10/6
4	1	1	0^2	10/8
5	3	1	2^2	14/10
6	3	5	$(-2)^2$	18/12

$\tau(0) = 0$

$\tau(a) = \frac{1}{12}(1^2+3^2+0^2+0^2+2^2+2^2) = 1.5$

$\tau(2a) = \frac{1}{10}(2^2+3^2+3^2+2^2+2^2) = 3$

$\tau(3a) = \frac{1}{10}(2^2+3^2+3^2+4^2+0^2) = 3.8$

Figure 2. Example Calculation of a Semivariogram (after Delhomme, 1975).

Z = measured data point at specified locations (L)

x_i = location in space

$\tau(h)$ = semivariogram of x_i (L^2)

Different types of geostatistical analyses require their own optimal well/sampling network. Typically, mapping (kriging) requires rather uniformly distributed data points to produce a uniform error of the kriged variable. However, the determination of the spatial structure of the variable (semivariogram) requires a certain number of closely spaced wells. Guidelines on how to develop a good data base for these different types of geostatistical analyses exist in the literature. Olea (1984) outlines practical guidelines for choosing an optimal sampling network for kriging. A detailed discussion on selection of a sampling network for empirical determination of a semivariogram is given by Russo (1984) and Warrick, et al. (1987).

2. WELPLAN Program

Because most bioreclamation activities are conducted in sites not exceeding approximately 1 hectare in size, the test site dimensions were selected to be approximately 100 by 100 meters. The well locations were selected based on the following nine planned activities:

1. Conducting a large-scale recirculation tracer test on the scale typical for bioremediation of jet-fuel spills;

2. Monitoring the pathway of tracer transport between the injection and withdrawal wells during large-scale tracer test;

3. Conducting a series of small-scale tracer tests on the scale of the averaged dimensions for the gravel and sand lenses;

4. Performing large- and small-scale pump tests with adequate well coverage to detect any anisotropy in the hydraulic conductivity field;

5. Achieving sufficient well coverage of the main test area to adequately define boundary conditions required to accurately apply groundwater models in the vicinity of the main area;

6. Determining the depositional trends of the sediments;

7. Determining the geostatistical structures of the hydraulic conductivity field;

8. Determining the two- and/or three-dimensional structure of the hydraulic pressure and hydraulic conductivity fields; and

9. Maintaining reasonable cost for the well installation program.

Because of the complexities associated with optimizing the well locations with respect to the nine planned activities, TVA and GeoTrans, Inc., a subcontractor, developed the computer program WELPLAN. WELPLAN's purposes are to determine which well network in a group of well networks has the best well location with which to calculate a semivariogram, and to develop a well network given a set of constraints for well positions.

WELPLAN receives as input the number of existing wells, the number of new wells that are to be used to improve the data set for kriging, the number of wells to be used to improve the data set for the semivariogram, the boundaries for the well network location, the lag distance, and the weights assigned to the criteria on which the well locations are evaluated. For the test site, a unit lag distance of 3 meters was used in WELPLAN and the following three criteria were used to rank each well network configuration under consideration: (1) a sufficient number (>10) of paired data points are available for every lag distance which is a multiple of 3 meters; (2) the actual average lag istance for each set of data points does not deviate more than 0.2 m from the desired lag distance for that set of data points; (3) the variance in the lag distance for each set of points is less than 0.5 m.

TVA used WELPLAN interactively to develop the well network. Steps used to design the well network were as follows. The first 17 wells were selected to provide uniform coverage across the site and well locations suitable for conducting a large-scale four-well recirculating tracer test and for kriging. The next 10 well locations were selected primarily to improve the semivariogram calculations. The next 9 well locations were selected with considerations 2, 3, 4, and 7 listed above. The last well (Well 37) was located adjacent to Well 28 so that the effects of the well installation method on well performance could be investigated.

Figure 3 illustrates the well network. In designing the network, TVA ran WELPLAN approximately 600 times. The 37 wells provide for 666

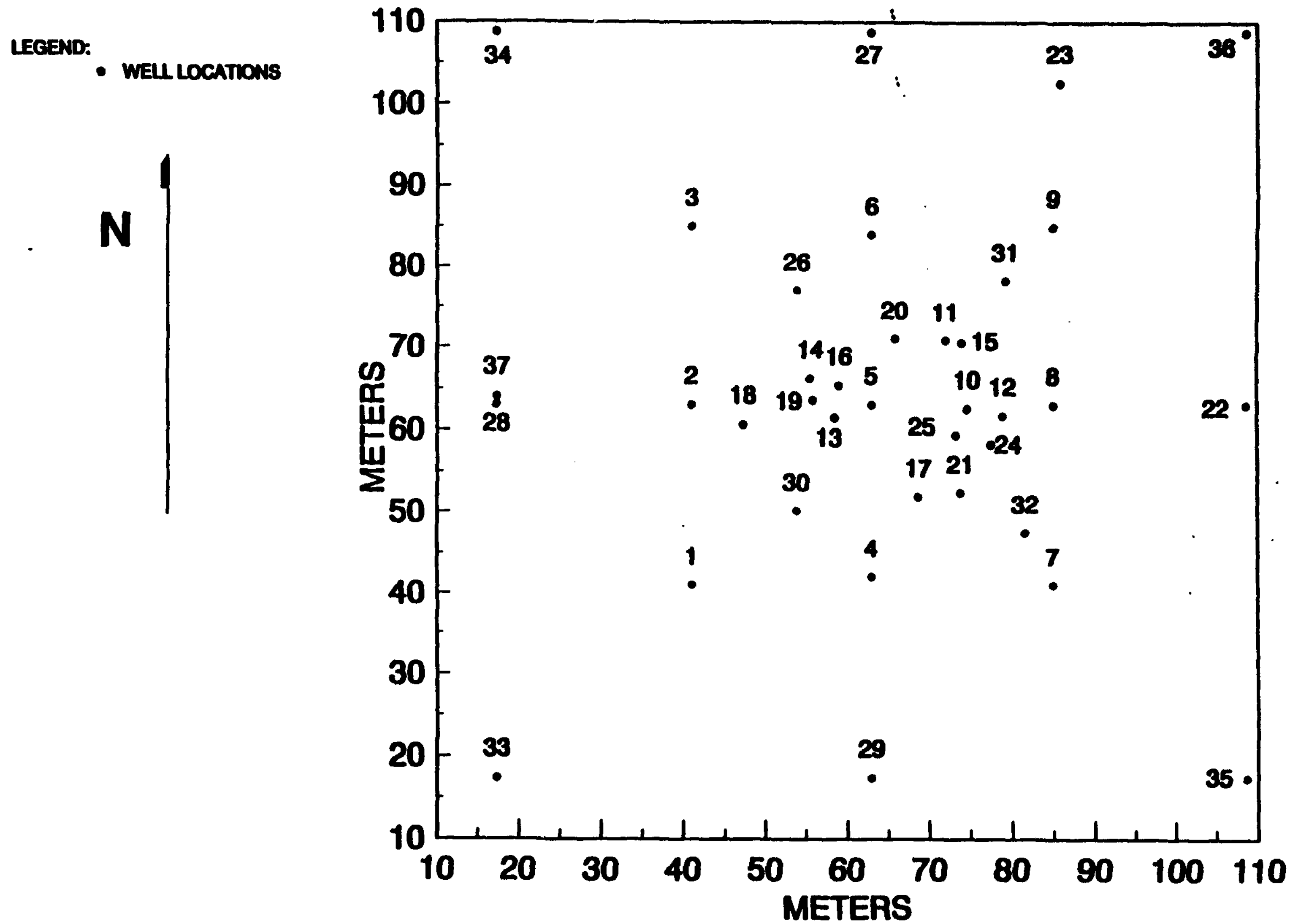


Figure 3. Final Well Network.

well pairs (i.e., 37*36/2). Figure 4 illustrates the distribution of the well pairs as a function of lag distances and the angles between the wells. The angles between the wells are measured clockwise from the north and are important with regard to Objectives 4 and 7 listed above.

C. WELL INSTALLATION

1. Well Installation Methods

For this project, four drilling methods were used: cable tool; rotary drilling; air percussion; and hollow-stem auger. To understand the potential advantage/disadvantage of each method a summary of each is provided. A thorough description of each is given by Driscoll (1986).

a. Cable Tool

Cable tool drill rigs operate by repeatedly raising and dropping a heavy string of drilling tools into a borehole. The primary drilling tools are the drill bit, the drill stem, and the cable. The drill bit is usually massive and heavy to crush and mix the materials encountered. The drill stem provides additional weight, and its length helps to maintain a straight hole. The cable is used to lift and to drop the drill bit and drill stem. The drill bit crushes and loosens the geologic formation until a slurry exists at the bottom of the well. When the penetration rate of the bit lessens, the slurry is removed from the borehole by a sand pump or bailer. This process is repeated at intervals.

b. Rotary Drilling

Direct rotary drilling methods were developed mainly to reach greater depths and increase drilling speeds. The borehole is drilled by rotating a bit. Cuttings are removed continuously by circulating drilling fluid as the bit penetrates the formations. Primary drilling tools are a drill bit, drill casing, and pump that recirculates the drilling fluid. The most common drill bit is a tricone bit with conically-shaped rollers on spindles and bearings set at an angle to the axis of the bit. The drill casing transmits the rotating action and the drilling fluid.

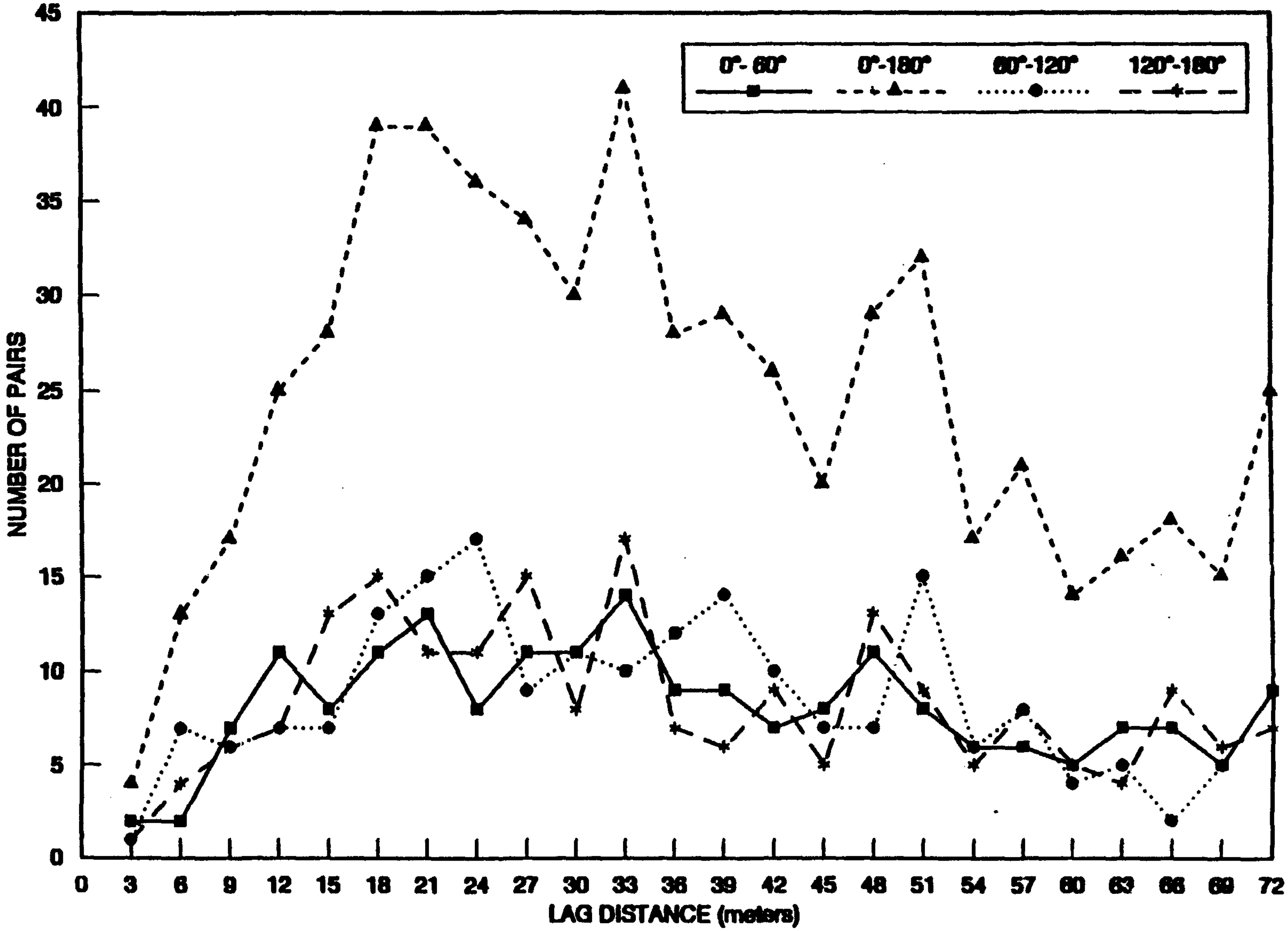


Figure 4. Number of Well Pairs for Each Lag Distance.

The drilling fluid is pumped down through the inside of the drill casing, to the drill bit. The recirculation pump provides enough force to push the drilling fluid down through and up through the annulus around the drill casing so that the cuttings will be transmitted to the surface. At the surface, the drilling fluid travels through a slurry of pit so that the cuttings will settle out. Drilling fluids include air, water, bentonite slurries, and other prepared mixtures. Drilling fluids are important because they affect the transport of the cuttings, the stabilization of the borehole, and the lubrication of the drill bit.

c. Air Percussion

The air percussion drilling method creates a borehole by breaking up the geological formation and displacing it with a high-pressure flow of air. Percussion type drilling tools include an air compressor and rigid air pipe. The rigid air pipe serves to guide the flow of air to the bottom of the hole. The air compressor provides the proper amount of air flow and backpressure to displace and lift the cuttings from the bottom of the borehole to the surface.

d. Hollow-Stem Auger

The hollow-stem auger drills by rotating a corkscrew-shaped drill casing into the ground. The primary drilling tools of this method are the bottom plug, the cutting bit, and the auger flights. The auger flights are drill casings around which is a continuous spiral-shaped cutting blade. The cutting bit is attached to the bottom of the auger flights and, when rotated, loosens the geological formation. The bottom plug prevents the cuttings from entering the inside of the auger flights. As the auger flights turn downward, the corkscrew action provided by the spiral-shaped cutting blade lifts the cuttings to the surface.

2. Advantages and Disadvantages of the Methods

The primary objective of the drilling method was to install a fully screened 5.2-cm PVC well at a reasonable cost and with minimal soil disturbance. A secondary objective was to obtain split-spoon soil

samples. For the cable tool, direct rotary, and air percussion drilling methods, a drill casing was periodically advanced at 1.5-meter increments ahead of the drilling to prevent the collapse of the borehole. Once the drill casing (or auger flight) reached the Eutaw clay formation at the aquifer's base, the PVC well was anchored and the drill casing (or auger flight) was withdrawn, leaving the well in place. Because of insufficient space between the outside of the borehole and the casing (or auger flight) no sand packs were used. Consequently, aquifer collapse was relied on to provide a good contact between the aquifer and the well.

Before the MADE site project, Rehfeldt, et al. (1989), conducted borehole flowmeter surveys at 36 fully screened wells. These wells were installed by the hollow-stem auger or air percussion drilling method. Most wells were installed by the air percussion method. The only justification offered by Rehfeldt, et al. (1989), for selecting the air percussion method is as follows:

> "Prior to testing, we suspected that the preferred method of well installation would be the [air percussion]. Admittedly, the method is slow and hence more expensive than augering, but the extent of aquifer disturbance is much less. Hence, the hydraulic conductivity obtained from a well installed by [air percussion] is likely to represent the 'true' aquifer hydraulic conductivity."

Rehfeldt, et al. (1989), do not support the statements with field data. Admittedly, the logic behind the statements is reasonable; the drill casing for the air percussion method is 8.9 cm whereas the outside diameter for the 7.6-cm ID hollow-stem auger (needed for 5.2-cm diameter well) is 15.2 cm. The air percussion method also results in significantly less soil mixing and removal than the augered method. However, one possible and major disadvantage of the air percussion method is that driving the drill casing may compact the soil around the well. This compaction would affect the soil's hydraulic properties values and would not be completely removed by well development.

The five reconnaissance wells were installed by air percussion in the same manner used by Rehfeldt, et al. (1989). Once the test site was selected, alternative methods using a drill casing were examined for three reasons. First, the air percussion method does not permit

collecting soil samples. Second, the air percussion method sprays cuttings and groundwater in the vicinity of the drilling activity--this spraying could pose a health threat at a contaminated site. Finally, the air percussion method was relatively slow in comparison to other drilling methods (approximately 1 well per day).

The alternative methods evaluated for improving the drilling methods were cable tool and direct rotary. Both of these methods permit the collection of soil samples. However, the cable tool method was slower and required a greater outer diameter of the drill casing compared to air percussion. The direct rotary method was faster than the air percussion method but occasionally had to use water instead of drilling mud to free the casing and drill bit. When it was used, drilling mud did irrepairable damage to the wells. Consequently, these wells had to be reinstalled. Table 6 lists the major advantages and disadvantages realized for each drilling method.

TABLE 6. MAJOR ADVANTAGES AND DISADVANTAGES OF EACH WELL INSTALLATION METHOD FOR SHALLOW ALLUVIAL TERRACE DEPOSITS

Well Method	Major Advantages	Major Disadvantages
Hollow-Stem Auger	- about 3 times faster than fastest drill casing method - split-spoon samples easily obtained	- potentially more removal and disturbance of soil than other methods
Air Percussion	- smallest drill casing OD (7.5 cm) - simplest method and most dependable in bad weather	- soil sampling not possible - cuttings are sprayed around well
Direct Rotary	- fastest method with drive casing	- occasional use of drill muds required - not well-suited for driving drill casing ahead of borehole
Cable Tool	- best opportunity to log borehole lithology	- largest drill casing OD (11.5 cm) - slowest drill casing method - trouble with removing drill casing

D. WELL INSTALLATION, CONSTRUCTION, AND DEVELOPMENT

1. Well Installations at the Test Site

The final well network contains 37 wells (see Figure 3). The four well drilling methods discussed previously were used to install the wells. In February 1988, TVA installed the first 3 wells using the air percussion method. The air compressor operated at 110 psi and at a flow rate of 20 m^3/min. The drill casing was flush-jointed and had a 7.5-cm OD. During November and December 1988, Graves Well Drilling, Sylacauga, AL, used a Bucyrus-Erie cable drill rig to install 7 wells. The drill casing had a 10-cm OD but 11.5-cm OD casing couplings. In December 1988, Law Engineering, Birmingham, AL, installed 11 wells by the rotary method with a Failing 1500 rotary wash drill rig. The drill casing was flush-jointed with a 10-cm OD. In April 1989, TVA installed 11 additional wells by the air percussion method and Springer Engineering, Starkville, MS, installed 5 wells by the hollow-stem auger method with a CME 65 drill rig. The hollow-stem auger had a 9.0-cm ID and a 15-cm OD.

During the well drilling, major problems occurred at Wells 8, 4, 6, and 13. At Well 8 on 9 November 1988, the cable tool rig drove the drill casing to a depth of 39 feet but could not withdraw the drill casing. On 21 November 1988, a crane was mobilized to retrieve the drill casing. The long delay in freeing the drill casing may have adversely affected the aquifer properties in the vicinity of the well.

On 11 November 1988, the drill casing broke during its retrieval at Well 13. A new location for Well 13 was selected; presently 6 meters of steel casing exists at the original location of Well 13. The breaking of the drill casing was attributed to drilling a crooked hole (Law, 1989).

In December 1988, a light- to mediumweight mud (<150 lb/ft^3) was inappropriately used during a rotary wash well installation method at Well 4. The drilling mud, Super Gel X Extra High Yield Drilling Fluid, was a product of American Colloid Company and is nonbiodegradable. Law Engineering reported that their well development activities indicated that the introduction of the mud had no adverse affects on the hydraulics

of the well (Law, 1989). In December 1988, the drilling mud was used inappropriately at Well 6. At Well 6, the drilling and setting of the well progressed satisfactorily, but as the drill casing was retrieved from the hole, it was discovered that a 10-foot section had been lost. Law Engineering inserted the drilling mud to stabilize the borehole so the lost casing could be retrieved and the well set. Law Engineering reported that their well development activities could not remove the apparent effects of the drilling mud. One week after the installation of Wells 4 and 6, TVA performed single-well pump tests on the wells. TVA showed that both wells were irreversibly affected by the drilling mud. The dec ion was made to install new wells for 4 and 6 about 2 meters away from the original locations for Wells 4 and 6.

Table 7 lists the coordinates, installation methods, installation date, top of casing elevations, and drilling companies for the 37 wells in the network. These wells were constructed and developed according to procedures described in the next two sections. Figure 5 shows the well network corresponding to the drilling method used in the installations.

2. Well Construction Method

All 37 wells are constructed from Schedule 40 5.08-cm Triloc PVC pipe. The screened sections of the pipe have 0.025-cm slots spaced at increments of 0.317 cm. The slotted pipe has an open area of about 5 percent. At its bottom, each well has a 14-cm unslotted section of pipe below about 9 meters of slotted pipe. Above these sections, the wells vary in their constructions; however, every well has slotted pipe up to at least 0.5 meters from the ground surface. During the construction of each well, accurate notes of the position of slotted and unslotted sections of pipe were recorded.

Before the well construction materials were bought, serious consideration was given to wells with diameters slightly less than 10.1 cm to decrease the annulus between the well and the drive casing (or auger flights). The decision to use the 5.08-cm well pipe was based on the necessity to demonstrate the applicability of borehole flowmeter technology in 5.08-cm wells. This well size is common for groundwater

TABLE 7. WELL SPECIFICATIONS

Well	X (m)	Y (m)	Company	Well Type	Installation Date	TOC* MSL(m)
1	41	41	LAW	RW	11/23/88	65.18
2	41	63	LAW	RW	11/29/88	65.40
3	41	85	LAW	RW	12/02/88	65.51
4B	63	42	TVA	AP	4/11/89	65.38
5	63	63	TVA	AP	2/17/88	64.97
6B	63	84	TVA	AP	4/07/89	65.30
7	85	41	GRAVES	CT	11/09/88	65.12
8	85	63	GRAVES	CT	11/22/88	65.12
9	85	85	LAW	RW	12/04/88	65.36
10	74.59	62.52	LAW	RW	12/04/88	65.33
11	71.95	70.8	GRAVES	CT	11/15/88	65.01
12	78.9	61.66	GRAVES	CT	11/14/88	65.12
13	58.5	61.5	LAW	RW	12/06/88	65.15
14	55.52	66.17	GRAVES	CT	11/18/88	65.45
15	73.88	70.52	GRAVES	CT	11/15/88	65.02
16	59.03	65.32	LAW	RW	12/01/88	65.44
17	68.67	51.85	LAW	RW	12/06/88	65.05
18	47.28	60.61	LAW	RW	11/30/88	65.32
19	55.83	63.55	LAW	RW	12/01/88	65.52
20	65.81	71.05	GRAVES	CT	11/17/88	65.29
21	73.8	52.41	LAW	RW	12/05/88	65.09
22	108.7	63.0	TVA	AP	2/11/88	65.09
23	85.87	102.6	TVA	AP	2/18/88	65.01
24	77.5	58.3	TVA	AP	4/06/89	65.54
25	73.2	59.4	TVA	AP	4/06/89	64.87
26	53.93	77.05	TVA	AP	4/07/89	65.07
27	63.0	108.7	TVA	AP	4/05/89	65.58
28	17.3	63.0	TVA	AP	4/05/89	65.01
29	63.0	17.37	TVA	AP	4/05/89	64.92
30	53.88	50.16	TVA	AP	4/11/89	65.01
31	79.22	78.27	TVA	AP	4/10/89	65.47
32	81.60	47.44	TVA	AP	4/10/89	65.67
33	17.37	17.37	SE	HS	4/06/89	65.51
34	17.37	108.7	SE	HS	4/05/89	65.68
35	108.7	17.37	SE	HS	4/05/89	65.36
36	108.7	108.7	SE	HS	4/05/89	65.23
37	17.37	64.0	SE	HS	4/06/89	65.19

TVA - TENNESSEE VALLEY AUTHORITY
LAW - LAW ENGINEERING
SE - SPRINGER ENGINEERING
GRAVES - GRAVES DRILLING

RW - ROTARY WASH (10-cm OD); Number of RW wells = 11
AP - AIR PERCUSSION (9.0-cm OD); Number of AP wells = 14
CT - CABLE TOOL (11.5-cm OD); Number of CT wells = 7
HS - HOLLOW STEM AUGER (15-cm OD); Number of HS wells = 5
TOC - TOP OF CASING

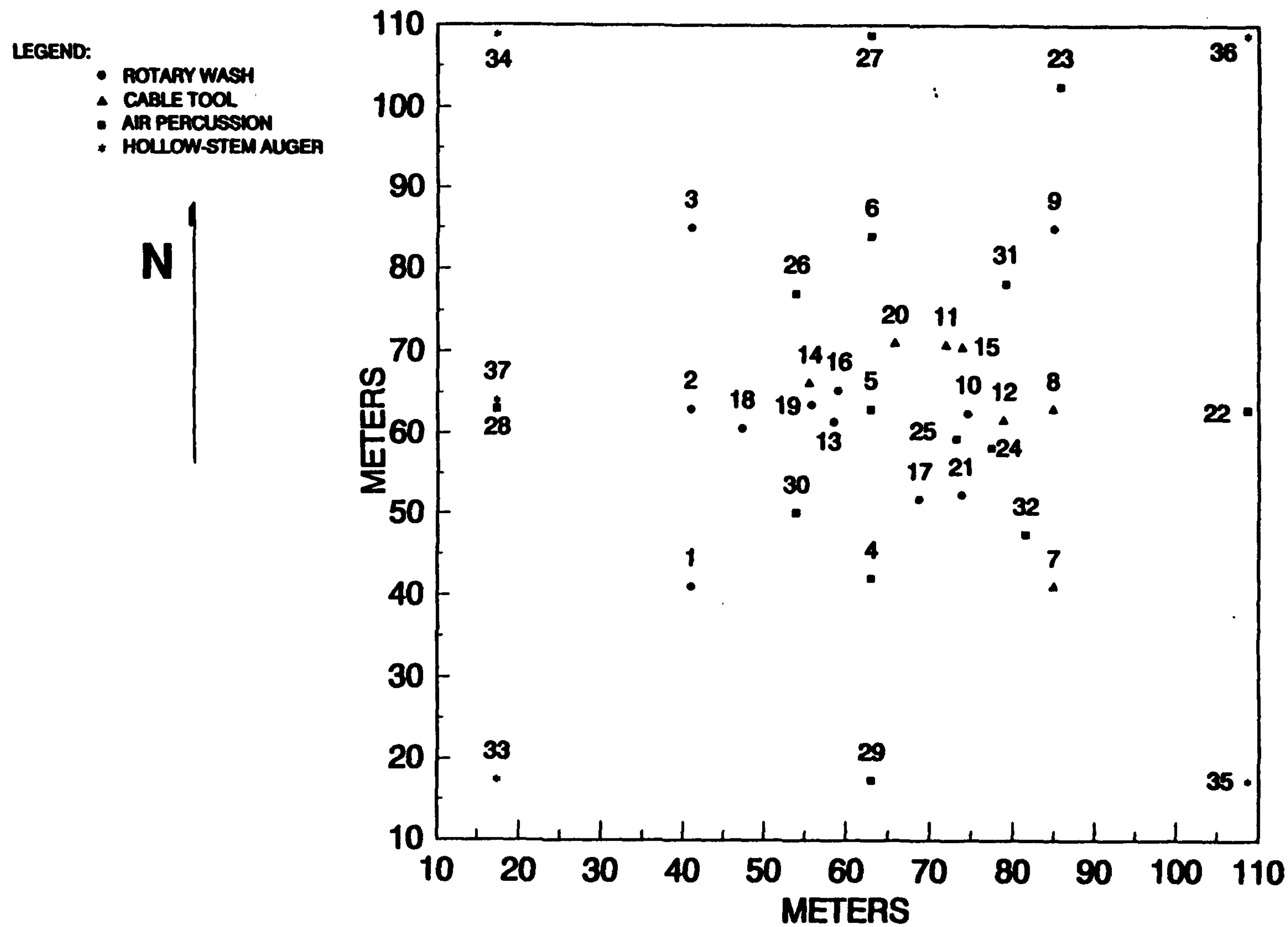


Figure 5. Well Network by Installation Method.

wells. Other investigators might consider pipe diameters greater than 5.08 cm to reduce the size of the well annulus.

During the construction of each well, four 0.06-cm OD plastic tubes were attached at designated locations on the well's exterior and extended to the top of the well. The tubes provide the capability for monitoring the hydraulic pressures during ambient conditions and during pumping by the method demonstrated by Young and Boggs (1988), and for obtaining groundwater samples during subsequent tracer tests. The plastic tubes were color-coded for ease of identification and attached in such a fashion as not to block any screened sections of the pipe.

Figure 6 is an example of a typical well installation. At each of the wells, the aquifer was permitted to collapse around the well and no extensive backing was performed with either the natural material or sand. In May 1989, all of the wells were grouted to ensure an adequate seal between the well and the ground surface. The grouting process included centering a 75-cm square piece of 1.3-cm thick plywood over the well and adding concrete around the well.

3. Well Development

Traditionally, well development has two broad objectives: (1) repair damage done to the formation by drilling operations so that the natural hydraulic properties are restored, and (2) to alter the basic physical characteristics of the aquifer near the borehole so that water will flow more freely to a well (Driscoll, 1986). Well development methods rely on applying the necessary force to cause movement and transport of the aquifer material around a borehole. These methods include overpumping, backwashing, mechanical surging, and air development. Driscoll (1986) offers a thorough discussion for each of these methods. Table 8 lists the benefits achieved by well development.

The purpose of pump tests for site characterization is to determine, as accurately as possible, the hydraulic conductivity distribution in the undisturbed aquifer. Consequently, the goal of well development for our project is primarily to repair damage done to the

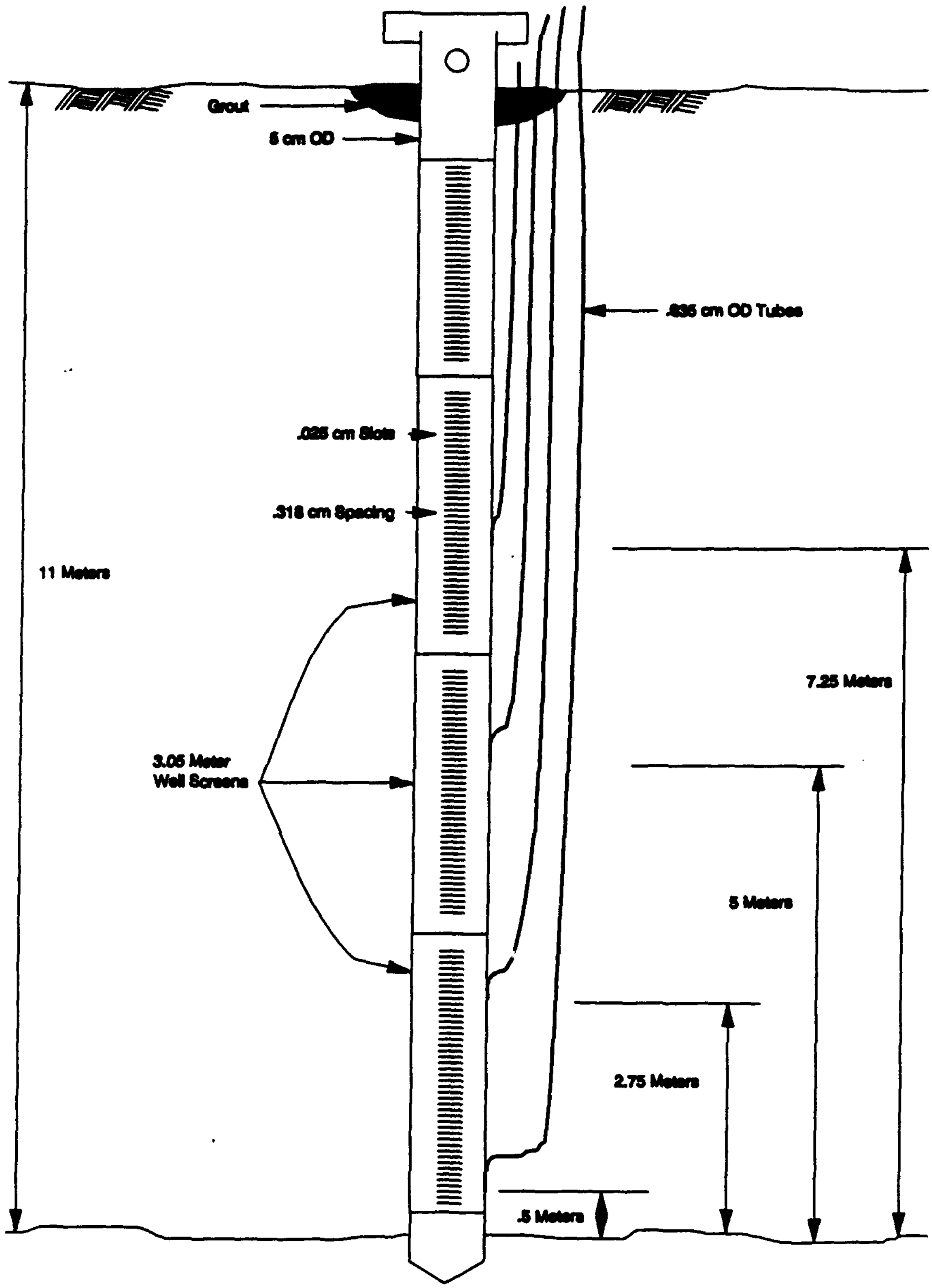


Figure 6. Example of a Typical Well Installation.

aquifer during well installation and to avoid increases in the hydraulic conductivity of the aquifer. At the MADE site, Rehfeldt, et al. (1986), conducted a series of field tests to determine the optimum method for well development. Rehfeldt, et al. (1986), conclude that a scheme including overpumping, backflushing, and mechanical surging led to adequate well development. However, Rehfeldt, et al. (1986), do not provide a recommended protocol for the well development.

TABLE 8. BENEFITS OF WELL DEVELOPMENT (from Driscoll, 1986)

(1) Reduce the compaction and intermixing of grain sizes produced during drilling by removing the fine material from pore spaces.

(2) Increase the natural porosity and permeability of the previously undisturbed formation near the [borehole] by selectively removing solids that have invaded the formation.

(3) Remove the filter cake or drilling fluid film that coats the borehole, and remove much or all of the drilling fluid and natural formation solids that have invaded the formation.

(4) Create a graded zone of sediment around the screen in a naturally developed well, thereby stabilizing the formation so that the well yields sand-free water.

Working with Rehfeldt, TVA developed the procedures list in Table 9 for well development. The surge block used in the procedures was approximately 0.3-meter long and consisted of a string of alternating layers of rubber gaskets and metal washers with diameters slightly less than the ID of the 5.2-cm wells. A well typically took about 2 hours to develop. These procedures were used at all of the 37 wells and should be appropriate for wells in unconsolidated materials at other sites.

TABLE 9. PROCEDURES FOR WELL DEVELOPMENT AT CAFB

(a) Place 2.5-cm hose at the bottom of the well and run the pump at maximum rate without drawing the water table down more than 5 feet;

(b) Continue step (a) until the effluent begins to clear;

(c) Once the effluent is clear, surge water into and out of the well by switching the pump on and off (notice no foot valves can be used) for about 5 minutes and then pump the well until it clears;

TABLE 9. PROCEDURES FOR WELL DEVELOPMENT AT CAFB (CONCLUDED)

(d) Repeat step (c) at the middle and at the top of the well;

(e) Once the surging of the well is completed, lower the TVA surge block (weighs approximately 2 pounds) to the bottom of the well;

(f) Quickly pull the surge block up about 1 meter and then allow it to drop back to its original position. Work the surge block up and down through this 1-meter vertical interval for 5 cycles. Apply the surge block to each 1-meter vertical interval in the well until the water table is reached;

(g) Repeat steps (e) and (f);

(h) Repeat steps (a) through (g) two more times.

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SECTION III

WELL EQUATIONS FOR HOMOGENEOUS AQUIFERS

A. THE THIEM EQUATION

The Dupuit assumption (Dupuit, 1848) is used to develop many analytical solutions to well flow problems in groundwater. This assumes that the hydraulic gradient in an aquifer is essentially equal to the slope of the free surface. Consequently, the piezometric head along any vertical line is a constant equal to the elevation of the free surface at that line. This assumption leads to the conclusion that groundwater flow is essentially horizontal and that vertical flow can be neglected.

Thiem (1906) used the Dupuit assumption to develop an analytical solution for steady flow to a well that is valid for confined and unconfined aquifers. Figure 7 assists in describing the derivation of the Thiem Equation. Figure 7 shows one-half of a cross section of the cone-of-depression surrounding a discharging well. Given the assumptions of steady flow and of Dupuit, Thiem used the law of continuity to deduce that equal quantities of water are discharged radially toward Well A through any two concentric cylinders that lie within the cone-of-depression. Thus, in Figure 7: $Q_{\text{Well A}} = Q_{r1} = Q_{r2}$. Under these assumed conditions Darcy's law may be expressed as a first-order differential equation in cylindrical coordinates (Lohman, 1952):

$$Q = -K2\pi rh\frac{dh}{dr} \tag{3}$$

Separating variables,

$$\frac{dr}{r} = -\frac{2\pi K}{Q}hdh$$

Integrating between r_1 and r_2, h_1 and h_2,

$$\int_{r_1}^{r_2}\frac{dr}{r} = -\frac{2\pi K}{Q}\int_{h_1}^{h_2}hdh,$$

hence:

$$\ln\frac{r_2}{r_1} = -\frac{2\pi K}{Q}\quad\frac{h_2^2-h_1^2}{2}$$

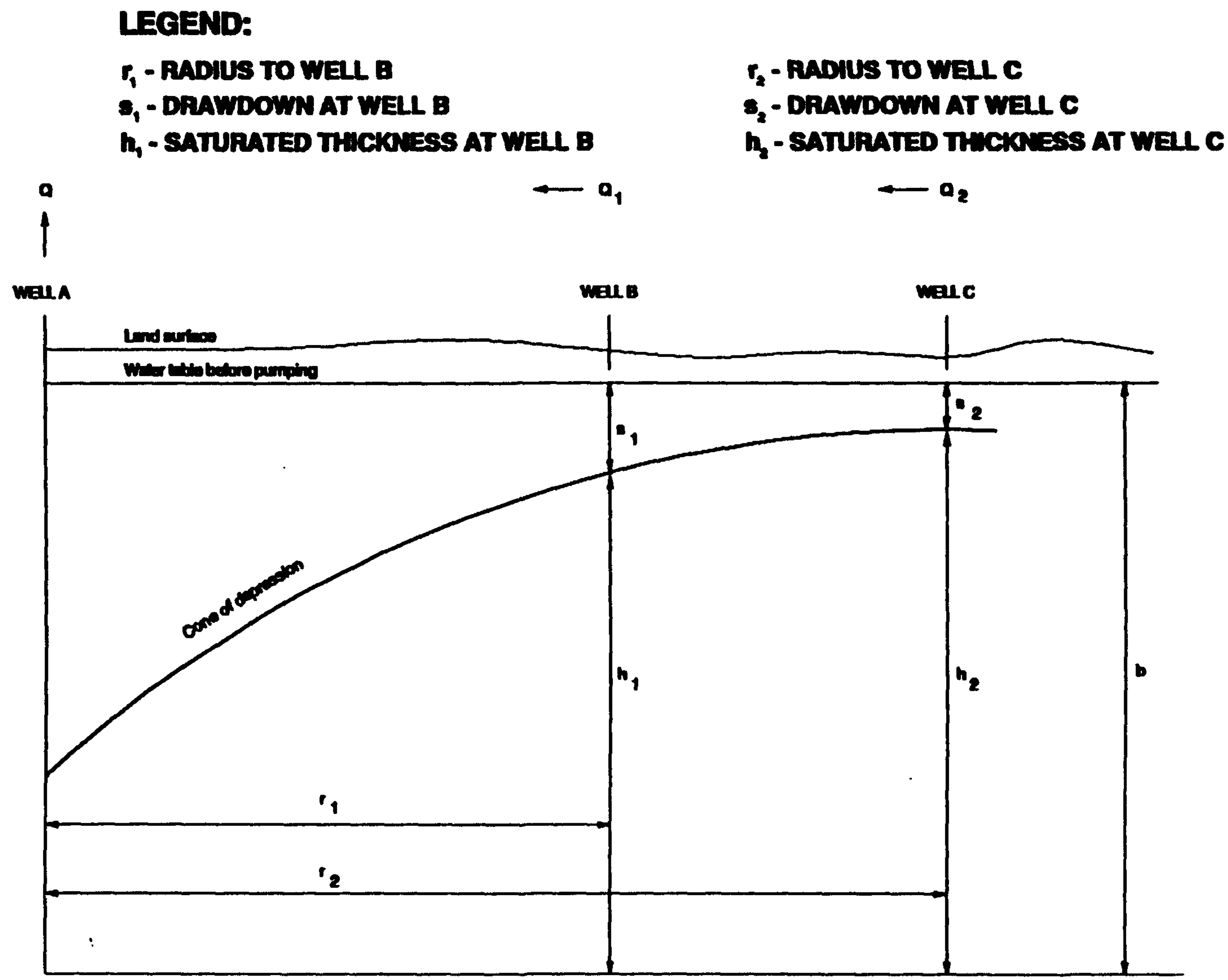


Figure 7. Cross-Section of the Cone-of-Depression Around a Discharging Well.

Converting to common logarithms and solving for K yields

$$K = - \frac{2.30Q \log_{10} r_2/r_1}{\pi(h_2^2 - h_1^2)} \tag{4}$$

Equation (4) is known as the Thiem (1906) Equation. For confined aquifers (where there is no dewatering) or in thick unconfined aquifers (where s is negligible compared to b), h_2+h_1 may be assumed equal to 2b. Then, as $h_2^2-h_1^2 = (h_2+h_1)(h_2-h_1)$, $h_2-h_1 = (s_1- s_2$, and $T = (K)*(b)$, Equation (5) may be written as (Lohman, 1952):

$$T = \frac{2.3 \quad Q \quad \log r_2/r_1}{2 \quad \pi \quad (s_1 - s_2)} \tag{5}$$

B. THE THEIS EQUATION

If the drawdown and vertical hydraulic gradients are small, the flow to the well in a homogeneous, confined will be nearly horizontal and the governing equation is given by

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \quad \text{or} \quad \frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{1}{D}\frac{\partial h}{\partial t} \tag{6}$$

where:

h = hydraulic head (L)
$T = \int_H K_h \, dz = K_p H$ = transmissivity (L^2/T)
$S = \int_H S_o \, dz + S_y = S_o H + S_y$ = storage coefficient (-)
S_y = drainable porosity = specific yield (-)
S_o = specific storage coefficient (-)
r = radial distance from the center of the well (L)
D = (T/S) = diffusivity (L^2/T)

By applying the principle of superposition, Equation (6) can be written in terms of drawdown, defined as the difference in hydraulic head between the nonpumping and pumping states

$$s(r,t) = h_R - h(r,t) \tag{7}$$

where:

h_R = hydraulic head in the aquifer prior to pumping
$h(r,t)$ = hydraulic head in the aquifer at radius r and time t

The equation for flow to a well, written in terms of drawdown, is

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t} \qquad (8)$$

Theis (1935) introduced a solution to Equation (8) by modifying a solution to heat conduction problems with a continuous point source. In the solution, see Equation (9), Theis states the following assumptions: (1) the aquifer is homogenous and isotropic; (2) the aquifer is infinite in areal extent; (3) the discharging well penetrates the entire aquifer thickness; (4) the well has an infinitesimal diameter; and (5) the water removed from storage is discharged instantaneously with a decline in the hydraulic head.

$$s(R,t) = h_r - h(r,t) = \frac{Q}{4\pi T} W(u) \qquad (9)$$

where:

$$W(u) = \ln\left(\frac{1}{1.781*u}\right) - \sum_{n=1}^{\infty} (-u)^n \frac{1}{n \cdot n!}$$

$$u = \frac{r^2 S}{4\ Tt}$$

Under the conditions where the assumptions are met, the Theis Equation, Equation (9), can be used to calculate the drawdown in a confined aquifer at any distance r from a well at any time t after the start of pumping given the aquifer properties, T and S, and the pumping rate Q. Similarly, by knowing the aquifer drawdown response over time or space and the discharge rate Q, Equation (6) can be used to calculate the aquifer properties, T and S. Traditionally, a graphical procedure is used to solve for T and S (Wenzel, 1942) by obtaining match points between the plots of t versus s and W(u) versus u.

C. THE COOPER-JACOB APPROXIMATION

1. Straight-Line Method

Cooper and Jacob (1946) showed that when the value of u is equal to or less than 0.05 (for most problems this value is usually assumed to be 0.01), the Theis solution reduces to Equation (10). Because the value of u becomes smaller as t increases and/or r decreases, Equation (10)

becomes valid when t is sufficiently large or r is sufficiently small (i.e., when the cone-of-depression approaches a steady-state drawdown for particular values of r and t). Equation (11) presents an alternative form of Equation (10). By considering S, T, Q, and r a constant in Equation (11) and recalling from differential calculus that a derivative of a constant is zero, one may obtain Equation (12).

$$s(r, t) = \frac{Q}{4 \pi T} \ln \frac{2.25Tt}{r^2 S} \tag{10}$$

$$T = \frac{2.3 Q}{4 \pi s} [\log\frac{2.25 T}{S} + \log t - 2 \log r] \tag{11}$$

$$T = \frac{2.30 Q}{4\pi \partial s/\partial(\log t)} \tag{12}$$

With the relationships shown in Equation (12), the transmissivity of the aquifer can be determined from a plot of drawdown versus time. As shown in Figure 8, drawdown data is plotted on semilogarithmic paper. Time t is plotted horizontally on the logarithmic scale, drawdown is plotted vertically on the arithmetic scale. The slope for the straight-line portion of the drawdown plot is the value for the partial derivative in Equation (12). Based on Equation (12), the transmissivity calculated for Figure 8 is 1,250 m^2/day.

In plotting the straight-line solution to Equation (12), Cooper and Jacob (1946) showed that by extending the straight-line until it intersects the line of zero drawdown, and noting the value of t at the intersection, the storage coefficient can be proven by Equation (13). Based on Equation (13), the storage coefficient for Figure 9 is 0.00019.

$$S = \frac{2.25 T t_o}{r^2} \tag{13}$$

where:

t_o = the intercept at time where drawdown equals zero

2. Derivation of the Thiem Equation

The Thiem Equation was derived by equating the flow through two cylindrical areas at different radii from the well. From Equation (10), the difference in drawdown at these 2 radii is:

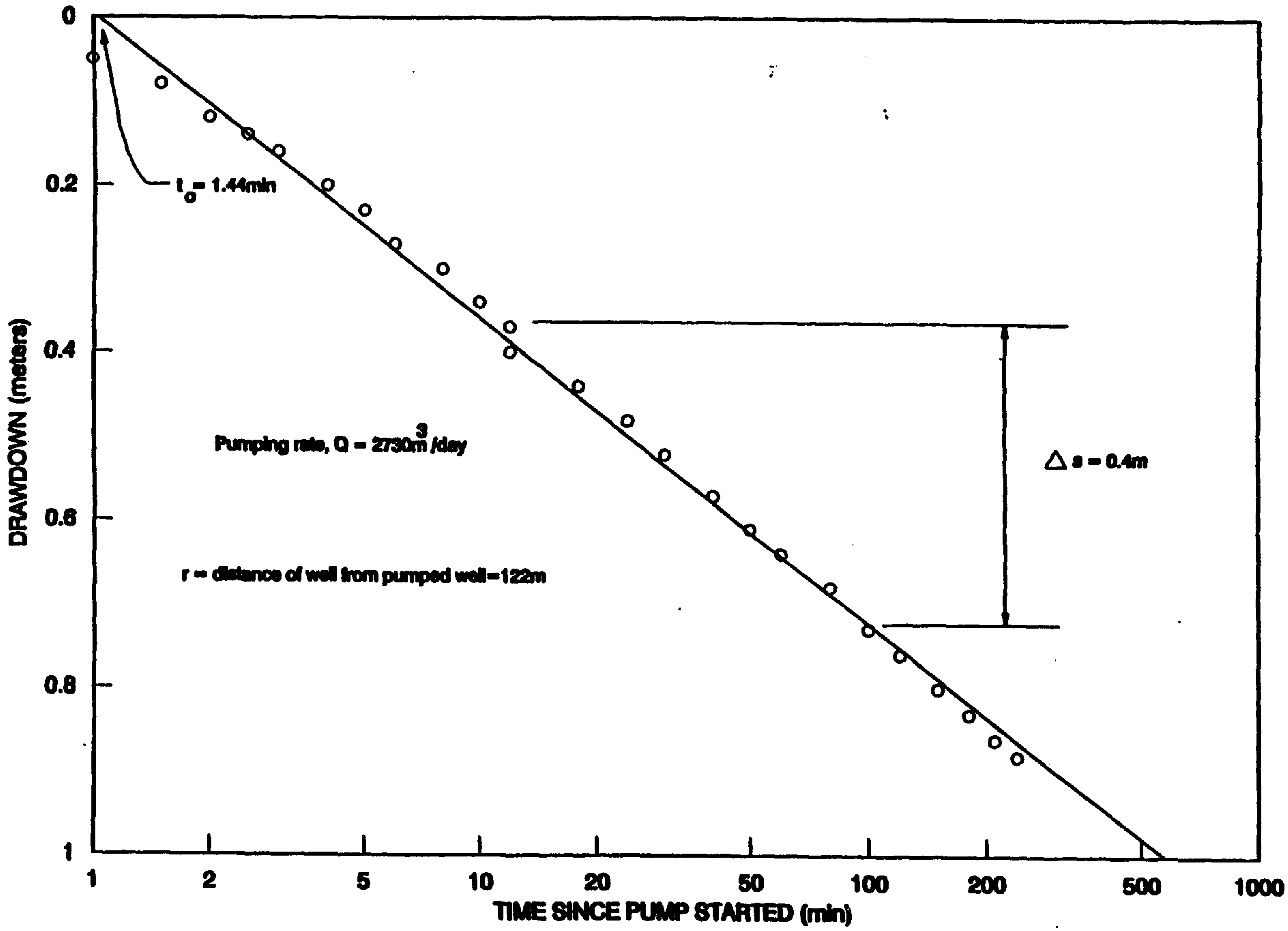


Figure 8. Drawdown Data Graphed on Semilogarithmic Paper (*from* Driscoll, 1986).

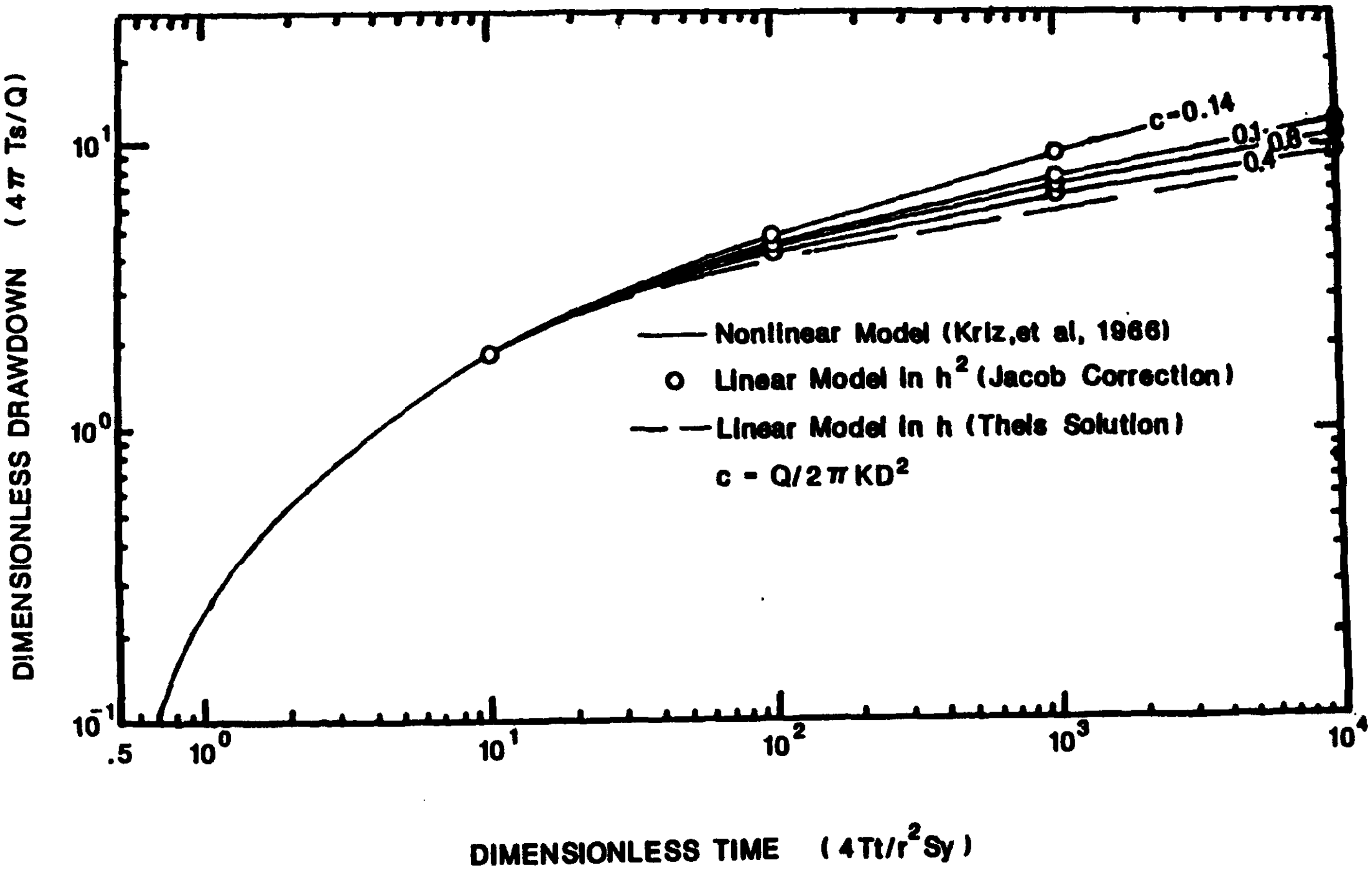


Figure 9. Comparison Between the Nonlinear Horizontal Model (Kriz, 1966) and the Linearized Models in h^2 (Jacob, 1963) and in h (Theis, 1935).

$$s_2 - s_1 = \frac{Q}{4 \pi T} [\ln \frac{2.25\ T\ t}{r_2^2\ S} - \ln \frac{2.25\ T\ t}{r_1^2\ S}]$$

simplifying to Equation (14), the Thiem Equation for a confined aquifer.

$$s_1 - s_2 = \frac{Q}{2 \pi T} [\ln \frac{r_2}{r_1}] \tag{14}$$

D. THE JACOB CORRECTION FACTOR

One of the problems in applying the Theis Equation to unconfined aquifers is that the equation essentially ignores the component of discharge contributed by the water released from storage drainage. In the vicinity of a pumping well the saturated thickness of an unconfined aquifer is decreased when water is released from drainage. For instances where the saturated thickness has diminished appreciably, Jacob (1963) has shown that the Theis solution should be applied only after a correction factor has been used for the drawdown data. Equation (15) expresses the correction factor that Jacob (1963) recommends to drawdown values that are large compared to the thickness of the unconfined aquifer.

$$s' = s - (s^2/2b) \tag{15}$$

where:

s' = corrected drawdown value (L)

s = measured drawdown (L)

b = thickness of unconfined aquifer (L)

Jacob (1963) developed Equation (15) by substituting the variable h in the Thiem Equation, Equation (4), with h-s for a steady-state flow problem. By using the same variable substitution into Equation (3), Equation (16) can be derived to solve for unsteady flow problems in unconfined aquifers (Elbakhbekhi, 1976). Equation (16) differs from Equation (9) in that the former is a linearized flow model in terms of h^2 whereas the latter is a linearized flow model in h.

$$s' = \frac{Q}{2 \pi T} \quad \frac{2}{c} (1 - [W(u) \times c]^{1/2}) \tag{16}$$

where:

$c = Q/(2\pi K b^2)$

To evaluate the accuracy of Equations (9) and (16), Elbakhbekhi (1976) compared the results of these equations to a numerical solution of the nonlinear Boussinesq Equation solved for a well discharge problem. The Boussinesq Equation was solved by the method proposed by Kriz, et al. (1966), in the form:

$$\frac{d^2\omega}{d\Sigma^2} + \left(\frac{1}{\Sigma} + \frac{1}{\sqrt{\omega}}\right)\frac{d\omega}{d\Sigma} = 0 \tag{17}$$

where: $\omega = (h/b)^2$, $\Sigma = (r^2 S_y)/(4Tt)$

Figure 9 compares the results of the three solutions. The results show very good agreement between the nonlinear, Equation (17), and the linear model in h^2, Equation (16). For instance, Elbakhbekhi (1976) shows only a 1 percent difference between the solutions of the nonlinear and linear in h^2 for $c = 0.08$ and $1/u = 10^5$. The agreement between the linear model in h, Equation (9), and the other two solutions, however, is poor. As either the value for u or for c increases, the deviation between Equation (9), Theis solution, and the other two solutions increases.

Figure 10 plots the same data utilized in Figure 9 for the nonlinear model and the linearized model in h. The differences between the two models is expressed as a difference in the well function W(u) as a function of the ratio between drawdown and the saturated thickness. For $s/B = 0.2$, there is a 10 percent difference which increases linearly to about 40 percent for $s/B = 0.8$; thus, the error introduced in the Theis solution by the linearization of the horizontal model is mainly a function of the ratio of drawdown to the initial saturated thickness s/B regardless of the value of c.

The important feature of Figures 9 and 10 is that the Theis solution will lead to errors of greater than 10 percent when applied to drawdown data from unconfined aquifers when the drawdown is greater than 20 percent of the aquifer's saturated thickness. In these cases, the Jacob correction factor should be used. The appropriate use of the Jacob correction factor for large drawdown values is confirmed by the agreement illustrated in Figure 10 between Equation (16) and the nonlinear solution to the Boussinesq Equation.

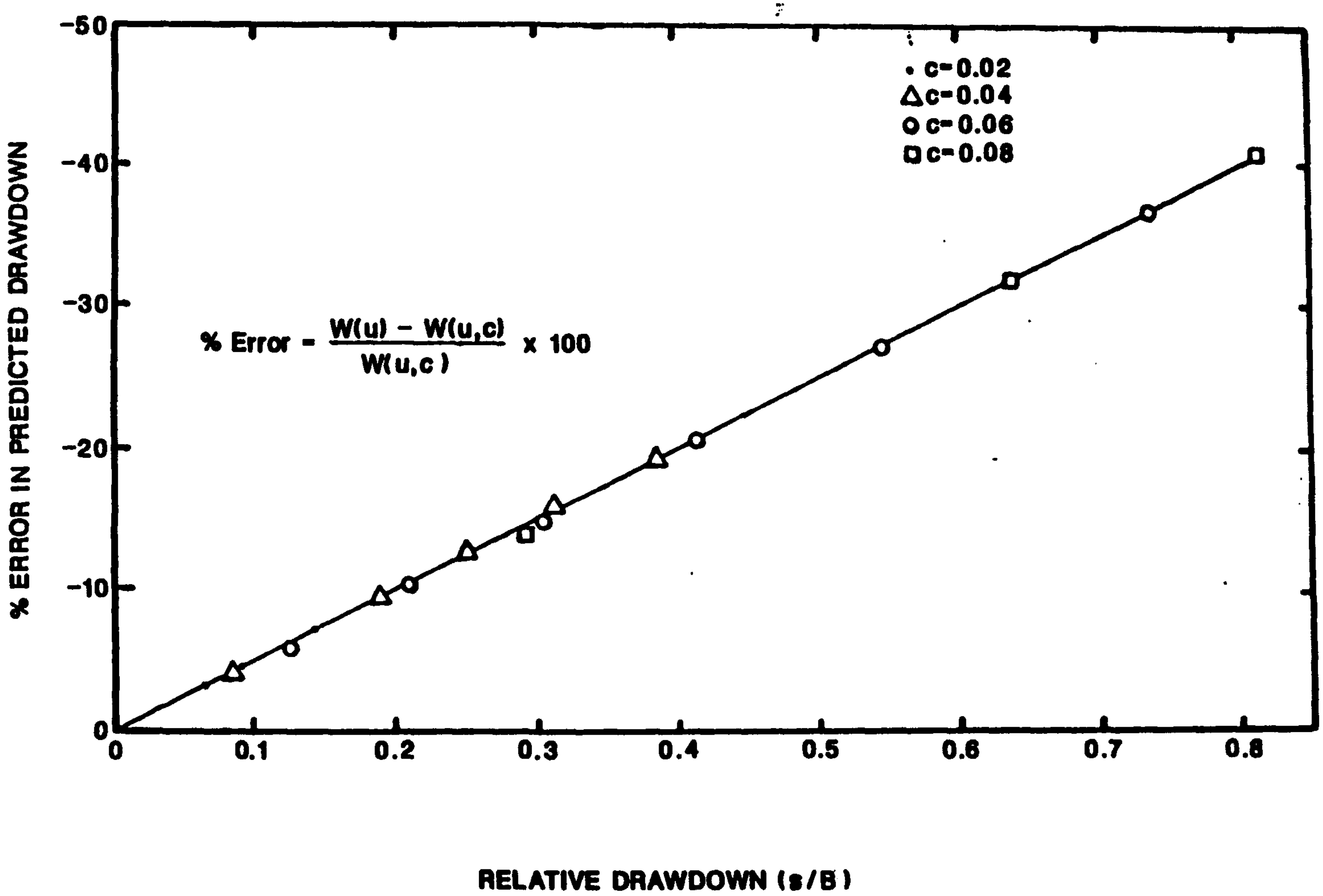


Figure 10. Comparison Between the Nonlinear Model (Equation 9) and the Linearized Model (Equation 16) in h.

SECTION IV

CONSIDERATIONS WHEN USING WELL EQUATIONS AT CAFB

A. HEADLOSSES AT THE WELL-AQUIFER INTERFACE

1. Skin Effect

Field evidence has shown that the specific capacity of a pumped well can be greatly affected by the hydraulic conductivity variations occurring in the zone immediately adjacent to it (Van Everdingen, 1953; Hurst, 1953). During well installation, this zone is disturbed from its natural state. A skin effect is produced when the hydraulic conductivity of the material around the well and the natural aquifer are different.

A negative skin effect refers to a reduction in the aquifer's hydraulic conductivity. Negative skin effects can be caused by the smearing of clay particles or the compaction of sediments during the advancement of the drill casing, and/or the intrusion of fines into coarse grain materials during improper well development. A positive skin effect refers to an increase in the aquifer's hydraulic conductivity. Positive skin effects can be caused by fractures from the drilling or the removal of fines from the sediments by the well development.

An important aspect of skin effect is its affect on the drawdown response of the borehole. The skin effect on the well's drawdown is typically assumed to be independent of time. However, Dudgeon and Huyakorn (1976) have shown by numerical experiments that the skin effect should not be considered as a constant until $1/u$ is greater than 10^4. For most applications, the limiting value of $1/u$ is less than the first few minutes of the pumping tests.

For steady-state flow, near the pumping well, Equation (18) can be used to predict the change in drawdown in the well that is produced by the skin effect (Dudgeon and Huyakorn, 1976; Hurst, 1953). Equation (19) can be used to estimate the error associated with predicting the average hydraulic conductivity of the well when the skin effect is ignored and when the Cooper-Jacob (1946) approximation is used.

$$s = \frac{Q}{2 \pi K b} [\ln(R/r_w) + (K/K_s - 1)\ln(r_s/r_w)] \tag{18}$$

$$\frac{K_c}{K} = \frac{\ln(R/r_w)}{\ln(R/r_s) + (K/K_s-1)*\ln(r_s/r_w)} \tag{19}$$

where:

- s = total drawdown
- R = radius of influence
- r_w = radius of well
- r_s = radius of skin effect
- K = true aquifer hydraulic conductivity
- K_s = hydraulic conductivity of skin effect
- K_c = calculated hydraulic conductivity for aquifer

The usefulness of Equations (18) and (19) are somewhat limited since parameters such as r_s and K_s cannot be measured in the field. However, these equations provide a valuable insight on the potential importance of skin effects. Figure 11 has been developed based on the values for R and r_w that are representative of the short- duration (20-30 minutes) pumping tests conducted for the borehole flowmeter surveys. Figure 11 shows type curves for the assumed skin radii of 1 and 10 cm over a range of six orders of magnitude for the skin hydraulic conductivity. Figure 11 shows that negative skin effects have more pronounced effects than positive skin effects, and significant errors can result in calculating hydraulic conductivity values from boreholes with moderate negative skin effects when the skin effects are ignored.

2. Well Losses

The drawdown in the pumping well is a combination of the headlosses accumulated in the aquifer and in the well. Jacob (1946) expresses the well losses in a pumping well in the form of $C \alpha Q^2$, where C is a constant dependent on the quality of the well installation and on the pumping rate. Hufschmied (1983) and Rehfeldt, et al. (1989), present a thorough discussion of the components that comprise well losses. These components include head losses attributed to contraction of the flow as it approaches the well screen, the movement of the flow

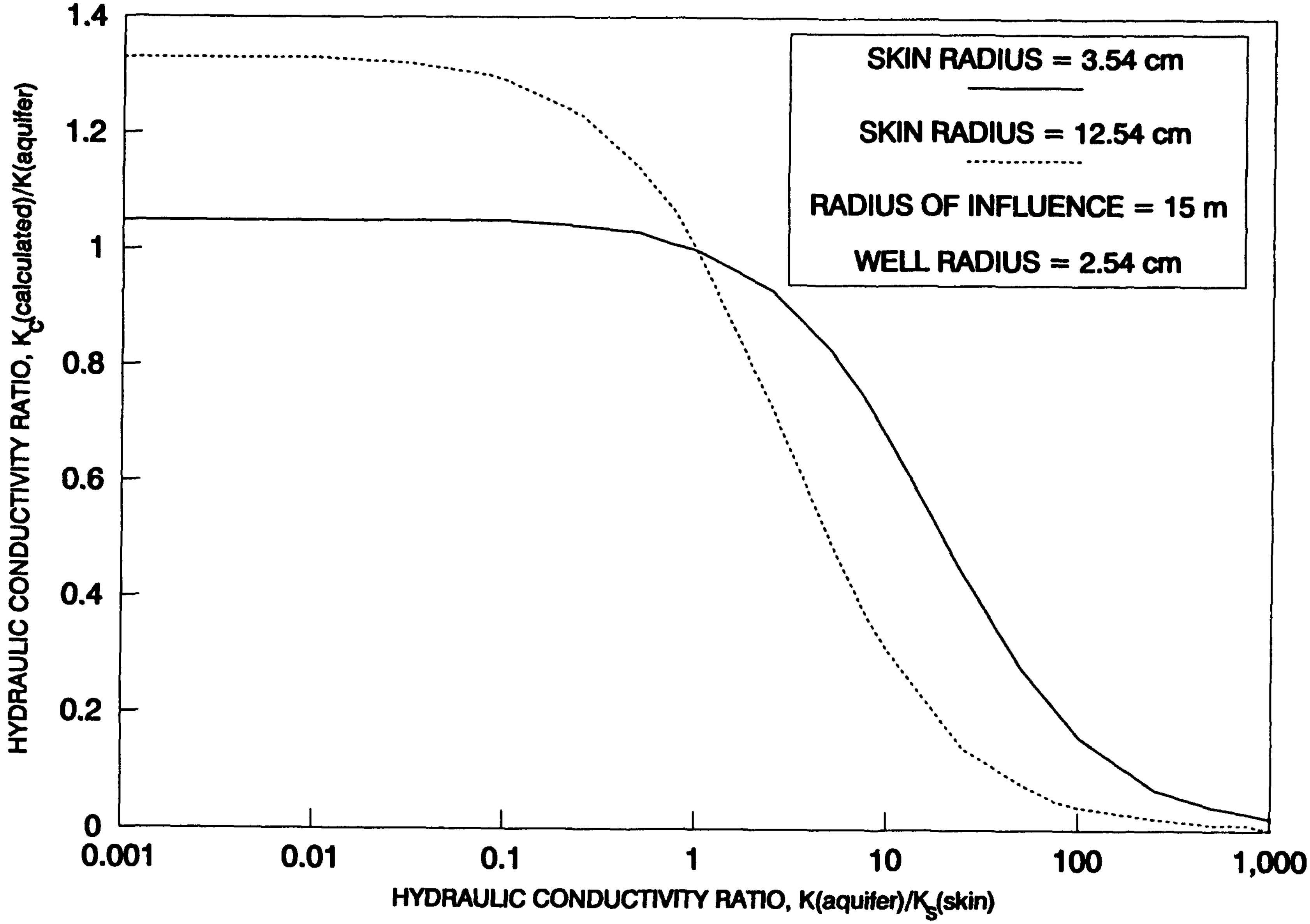


Figure 11. Type Curves for the Skin Effect.

through the well screen, the vertical movement of the flow through the well, and the constrictions caused inside the well by the discharge hose.

Driscoll (1986) states that: "field and laboratory tests show that the average entrance velocity of the water moving into the screen should not exceed 0.03 m/s. At this velocity, the friction losses in the screen will be negligible and the rates of incrustation and corrosion will be minimal." The average entrance velocity is calculated by dividing the discharge rate by the total area of the screen openings.

At the test site, the 5.2-cm OD wells have 6-meter screen lengths and a 4.2 percent total opening. These wells can be pumped at a rate of 76 L/min (20 gal/min) before the average entrance velocity of 0.03 m/s is exceeded. However, because of the nonuniformity in the hydraulic conductivities in alluvial sediments, one would expect that a pumping rate of 76 L/min (20 gal/min) at all wells, and even a lower rate at some wells, would induce entrance velocities exceeding 0.03 m/s.

B. AQUIFER HETEROGENEITIES

1. Previous Modeling Studies

Few studies have been done to address potential problems of applying the Theis Equation to heterogeneous aquifers. Warren and Price (1961) were among the first to investigate flow through heterogeneous aquifers; modeling effects of hydraulic conductivity variations on steady-state and transient pressure behavior in three-dimensional groundwater systems using Monte Carlo techniques. For log-normal permeability distribution with no spatial correlations, Warren and Price (1961) state that the most probable behavior of a heterogeneous system approaches that of a homogeneous system with an effective hydraulic conductivity equal to the geometric mean of the input distribution.

Vandenberg (1977), using a method similar to that of Warren and Price (1961), simulated the drawdowns in observation wells caused by a pumping well in a two-dimensional groundwater system. Based on an analysis of the modeling results, Vandenberg (1977) concluded: "the

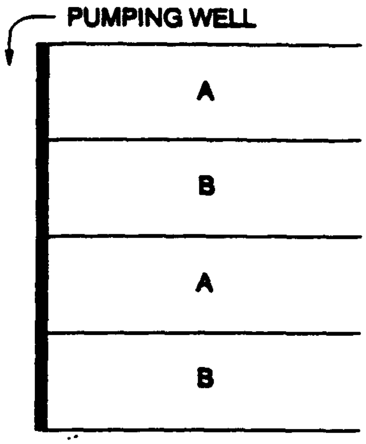
Theis analysis of time- and distance-drawdown, and the subsequent prediction of future water levels may be valid procedures in groundwater resources evaluation, even if the aquifer is not homogeneous as assumed in the theory, provided that the pump test is conducted for a sufficient length of time and the latter part of the time-drawdown curve is given more weight in the analysis."

The results of Warren and Price (1961) and Vandenberg (1977) essentially indicate that for their case examples, the Theis Equation applied to drawdown data at late times, provides a reasonable estimate of the average hydraulic properties of the aquifer at the regional scale. The studies did not address the usefulness of the Theis Equation at early times and did not model the drawdown response in an observation well for three-dimensional aquifers.

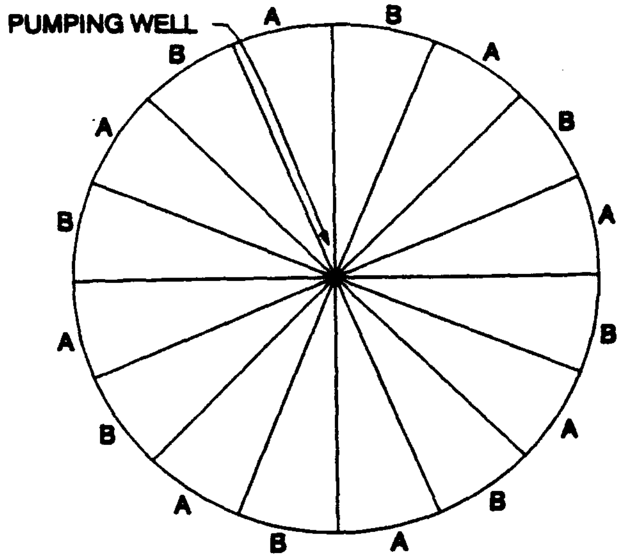
Butler (1986) performs a series of numerical simulations to rigorously determine the applicability of the Theis Equation in three-dimensional aquifers that includes variations of hydraulic conductivity with depth, angular position, radial distance, and a combination of depth, angular position, and radial distance (Figure 12). In an aquifer with a constant storage coefficient that has hydraulic conductivity variations perpendicular to the direction of the flow (Figure 12a and b), a pressure change will move faster through higher rather than lower zones of hydraulic conductivity. As a result, pressure change induced by a pumping well will not travel at a uniform rate outward in a heterogeneous aquifer. Differential pressure heads in aquifer zones create hydraulic gradients that cause crossflow among the zones. In general, crossflow will be from low to high permeability zones near the well and from high to low permeability zones far from the well. Butler showed that representativeness of transmissivities derived from pump-test analysis depended on whether or not crossflow among different aquifer material has occurred long enough to produce equilibration within the pressure field.

2. Sources for Potential Error

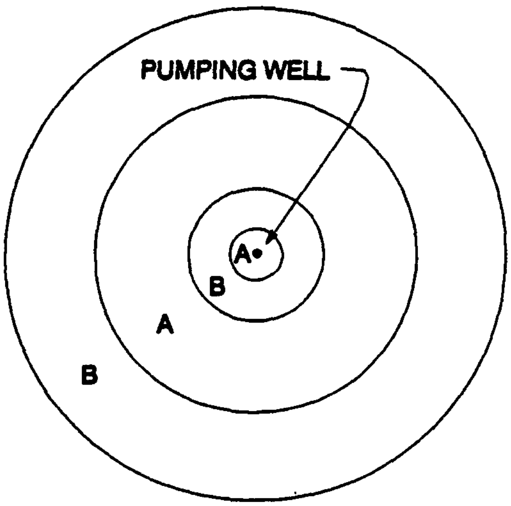
The Theis Equation is a solution to Equation (6), which is based on the assumptions of homogeneity and isotropy. Modifying Equation (6)



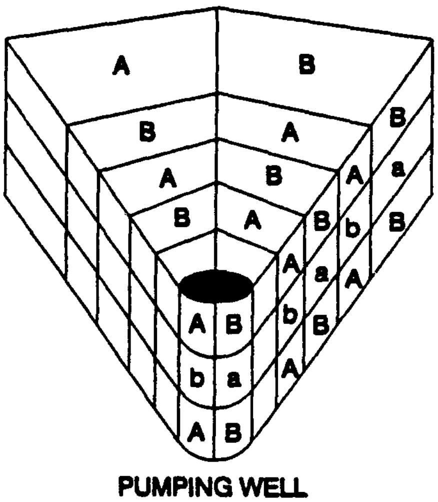
a. Vertical Variations



b. Angular Variations



c. Radial Variations



d. Vertical, Angular, and Radial Variations

Figure 12. Types of Hydraulic Conductivity Variations.

to address nonhomogeneous anisotropic system yields Equation (20). This permits variations in hydraulic conductivity with respect to depth, angular position, and radial distance. In applying the Theis Equation to drawdown data in heterogeneous aquifers, one implicitly assumes that crossflow among the different aquifer materials is insignificant and that no significant trends exist in the radial direction in the hydraulic conductivity field. If any of the underlined terms in Equation (20) are not negligible, then the Theis Equation leads to incorrect results.

$$\underline{\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)} + K\frac{\partial^2 h}{\partial r^2} + \underline{\frac{\partial K}{\partial r}\frac{\partial h}{\partial r}} + \underline{\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K\frac{\partial h}{\partial \theta}\right)} + \frac{K}{r}\frac{\partial h}{\partial r} = S\frac{\partial h}{\partial t} \qquad (20)$$

where:

θ = angular position

Even if the underlined terms on the left side of Equation (20) are negligible, the potential for biasing calculated aquifer parameters still exists. This is due to the different analytical methodologies that emphasize portions of the time-drawdown curve in different ways. Whereas a Theis curve-fitting approach emphasizes matching the total drawdown over time, the Cooper-Jacob straight-line approach emphasizes matching the slope of the time-drawdown curve at later times.

In most aquifer systems, the initial pumping withdraws water primarily from a localized area around the well. As a result, near the well a large portion of the total drawdown occurs within a relatively short time. Thus, the curve-fitting method is inherently more sensitive to the the aquifer's properties near the well than far from the well. At latter times, the rate of change in the drawdown at the well is more a function of the aquifer properties through which the cone-of-depression is passing rather than the aquifer properties near the well. Because it is based only on the slope of the time-drawdown curve at latter times, the Cooper-Jacob straight-line method is inherently more sensitive to the aquifer properties far from the well.

Butler (1986) has examined the potential source of error listed above and offers the following three conclusions based on his data input and numerical simulations:

"1. The traditional approach of pumping test analysis employing methods based on analytical solutions to [Equation 6] can be a viable approach in nonuniform aquifers of the type examined here. A pumping-test transmissivity is sensitive to hydraulic conductivity variations in the angular and radial directions. The sensitivity is not translated into a strong dependence on the angular or temporal location of the observations. Considerable dependence, however, may be found in the radial direction in the case of a [Theis curve-fitting] analysis. Therefore, the single parameter value calculated from a pumping test can be considered representative of the pump well, as long as the point of observation is at a relatively small, normalized radial distance from the well.

2. The specific purpose for which transmissivity value will be utilized should determine the analytical approach. If the local properties of the aquifer in the area surrounding the observation point are of concern, a Theis-based [curve-fitting] analysis should be used. If a large-scale average over the region is of interest, the Cooper-Jacob analysis should be employed, preferably over an interval at a large dimensionless time. (Butler defines dimensionless time as 1/u.)

3. When a transmissivity value is to be used as an effective value in a distributed-parameter model, application of the Cooper-Jacob analysis at large dimensionless times is the preferred approach."

SECTION V

TRANSMISSIVITIES AND STORAGE COEFFICIENTS FROM LARGE- AND SMALL-SCALE AQUIFER TESTS

A. OBJECTIVES

Aquifer tests include pumping or injecting water at designated well(s), measuring the aquifer's pressure response at observation wells, and applying well equations to the data to estimate the aquifer's hydraulic properties. Traditionally, aquifer tests have been the standard method used to determine the average hydraulic properties of aquifers and have been relatively expensive to conduct. A series of aquifer tests were conducted at the CAFB site to accomplish the objectives listed in Table 10.

TABLE 10. OBJECTIVES FOR THE LARGE- AND SMALL-SCALE AQUIFER TESTS

1. Determine Average Value of Transmissivity and Storage Coefficient for CAFB Test Site
2. Develop Method for Optimizing Design of Large-Scale Aquifer Tests
3. Develop an Objective and Simple Method for Data Analysis
4. Determine Appropriateness of Theis Equation and Cooper-Jacob Approximation for Heterogeneous Aquifers
5. Evaluate Usefulness of Large-Scale and Small-Scale Aquifer Tests to Characterize Aquifer's Heterogeneity
6. Develop Cost-Effective Method for Conducting and Analyzing Aquifer Tests

B. GENERAL APPROACH

Between June 1988 and August 1989, three large-scale and seven small-scale aquifer tests were conducted. Each of the large-scale tests included pumping Well 5 (the center well) for about 6 days at a rate sufficient to produce measurable drawdowns at most, if not all, of the wells. For each of the seven small-scale aquifer tests, a designated well within a well cluster was pumped for about 3 hours at a rate

sufficient to produce measurable drawdowns at radial distances of up to 6 meters.

The primary purpose of the large-scale aquifer tests was to determine the sensitivity of the calculated hydraulic properties to the pumping schedule and the method of data analysis. The primary purpose of the small-scale aquifer tests was to determine the sensitivity of the calculated hydraulic properties to the orientation of the pumping well to the observation wells.

Two important tasks associated with aquifer tests are maintaining a constant pumping rate and collecting accurate drawdown data in a timely fashion. For all of the aquifer tests, a positive displacement pump was used; and, the pumping rate was frequently measured. For each of the aquifer tests, continuous values of drawdown were measured by Druck transducers and recorded by Telog data-logging systems. The Druck transducers are accurate to within 0.3 cm. The Telog data-logging systems permitted logging at intervals equal to or greater than 1 second and a graphical display of the data at any time.

Another important task associated with aquifer tests is to systematically analyze the data in an unbiased manner. Traditionally the evaluation process has centered on visually matching the experimental pumping-test data to a theoretical drawdown curve to obtain values of transmissivity and storage coefficient. The manual method of curve matching can be cumbersome and labor intensive. Moreover, the method contains subjectivity that varies among geohydrologist. In order to improve the speed and the objectivity associated with aquifer test analyses, TVA developed the program WELTEST.

C. PROGRAM WELTEST

WELTEST is a computer program that automatically determines which values of transmissivity and storage coefficient produce a drawdown curve that best matches the experimental data set. Program WELTEST uses the method of nonlinear least-squares regression to obtain the best match. The concept of applying a computerized analysis to determine the "best"

transmissivity and storage coefficient was introduced by Vandenberg (1971). Vandenberg's (1971) program was specifically written for drawdown measurements in an observation well near a well pumping at a constant rate from a semi-infinite, nonleaky aquifer. An examination of the program reveals several potential problems among which is the inability to properly converge in some situations.

Since 1971, numerous programs (i.e., McElwee and Yukler, 1978; Chander, et al., 1981; Bardsley, et al., 1985) have been written to improve Vandenberg's approach. These programs differ in the type of well equations used and the speed and accuracy of the algorithms used to solve the nonlinear regression. In general, the logic and structure of these programs are very similar: the programs use partial derivatives of the well equations to drive the regression analysis. Because they use derivatives, each program is limited to a specific well equation and is computationally intensive when numerous experimental data points are used.

The WELTEST program was written to solve for best values of transmissivity and storage coefficient for either a confined or an unconfined aquifer, for either leaky or nonleaky conditions, and for constant or variable pumping rates. WELTEST does not account for any type of borehole storage or borehole skin effects. The WELTEST program algorithms are more computationally efficient than the algorithms used in the programs similar to Vandenberg's (1971). The modularity and speed of WELTEST results by using Broyden's Method (Benton, 1990) to develop derivative-free algorithms for locating extrema of nonlinear equations.

The input requirements for WELTEST include the experimental data, the distance to the observation well, the pumping schedule, the thickness of the aquifer, and whether the aquifer is confined or unconfined. The main output from WELTEST is the "best" values for transmissivity and storage coefficient. Optional output from WELTEST includes a sensitivity analysis for each parameter, a plot comparing the predicted and the observed pump-test curves, and/or a map of the residuals.

The map of the residuals provided by WELTEST illustrates the sensitivity of the predicted time-drawdown response to transmissivity and

the storage coefficient values. To create a map of the residuals, program WELTEST generates a series of hypothetical time-drawdown aquifer responses for different sets of transmissivity and storage coefficient values. For each of the time-drawdown responses, program WELTEST divides the difference in the areas between the predicted and observed time-drawdown response by the total area beneath the observed time-drawdown curve. For convenience, the residual is expressed as a percentage. A residual of 0.10 means that the difference between area of the predicted and the observed time-drawdown curves is 10 percent of the total area beneath the observed time-drawdown curve. A residual of 0.0 means that the predicted and the observed time-drawdown curves are exactly the same.

Figures 13 and 14 were created to demonstrate an application of WELTEST and the importance of the aquifer test design. The figures illustrate the residuals created for observation wells at different distances from the pumping well for a hypothetical aquifer with a transmissivity and a storage coefficient of 30 cm^2/s and 0.03, respectively. Figure 13 is for a constant pumping rate of 40 L/min for 24 hours, whereas Figure 14 is for a 2-hour-on and 2-hour-off pumping rate of 80 L/min for 24 hours. Figure 13 indicates that near the pumping well, the solution to the well equations are relatively insensitive to storage coefficient values. Similarly, for distances far from the pumping well, the solution to the well equations are relatively insensitive to transmissivity values. A comparison between Figure 13 and 14 shows, that at distances near the well, the sensitivities of the solution to the well equations to both storage coefficient and transmissivities are remarkably improved by pulsing the the pumping well. This means that by pulsing the pumping well, the aquifer's hydrologic properties can be better defined.

D. AQUIFER TEST 1

1. Test Description

Aquifer Test 1 consisted of pumping Well 5 at a constant rate and measuring the drawdown in all 37 wells. Pumping began on 18 May 1989 at 0800 hours and ended on 23 May 1989 at 0900 hours. The pump ran for

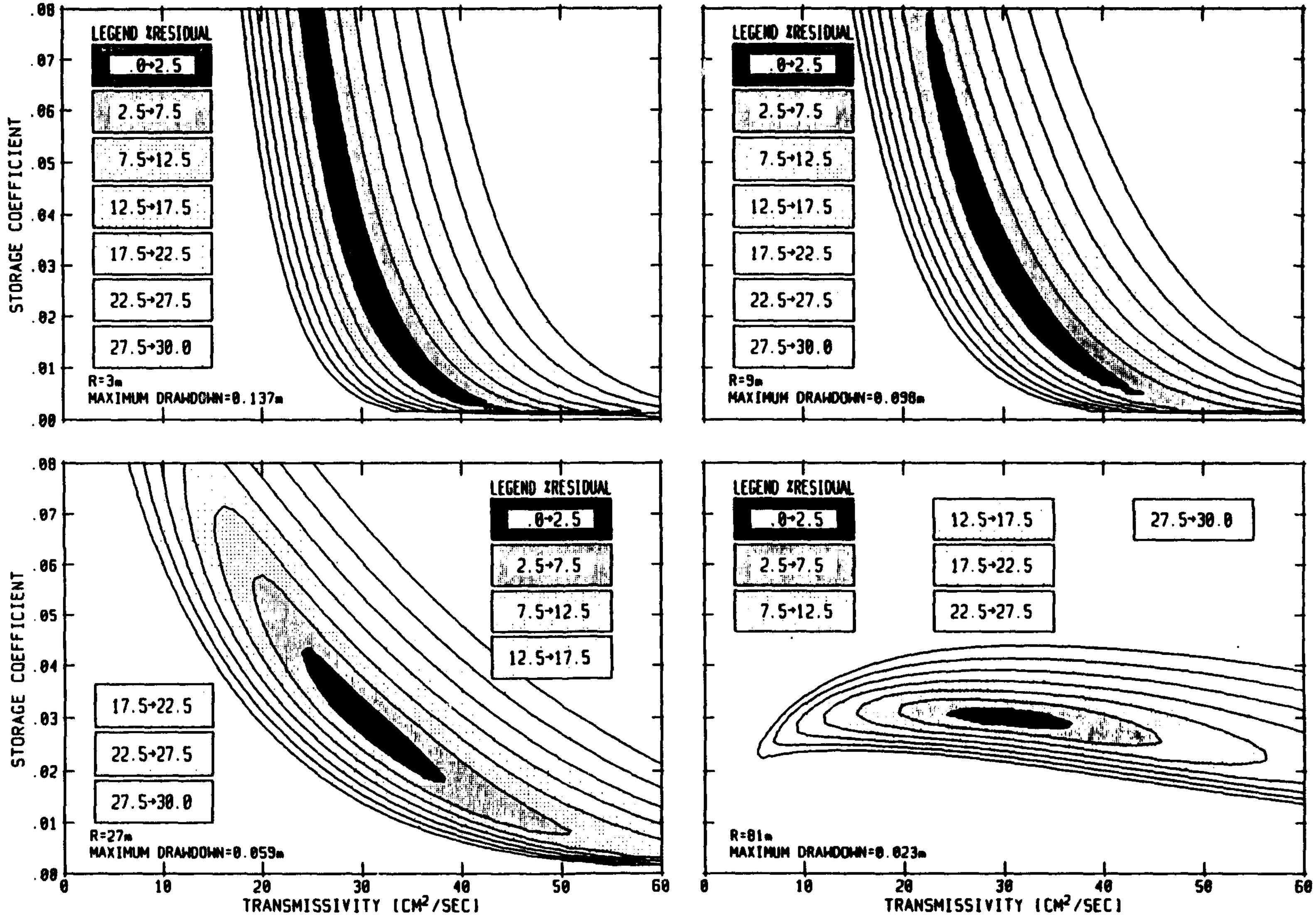


Figure 13. WELTEST Maps of the Cumulative Residual (as a Percentage) for an Aquifer Test With Constant Pumpage in an Idealized Homogeneous Aquifer With a Transmissivity and a Storage Coefficient of 30 cm^2/s and 0.03, Respectively.

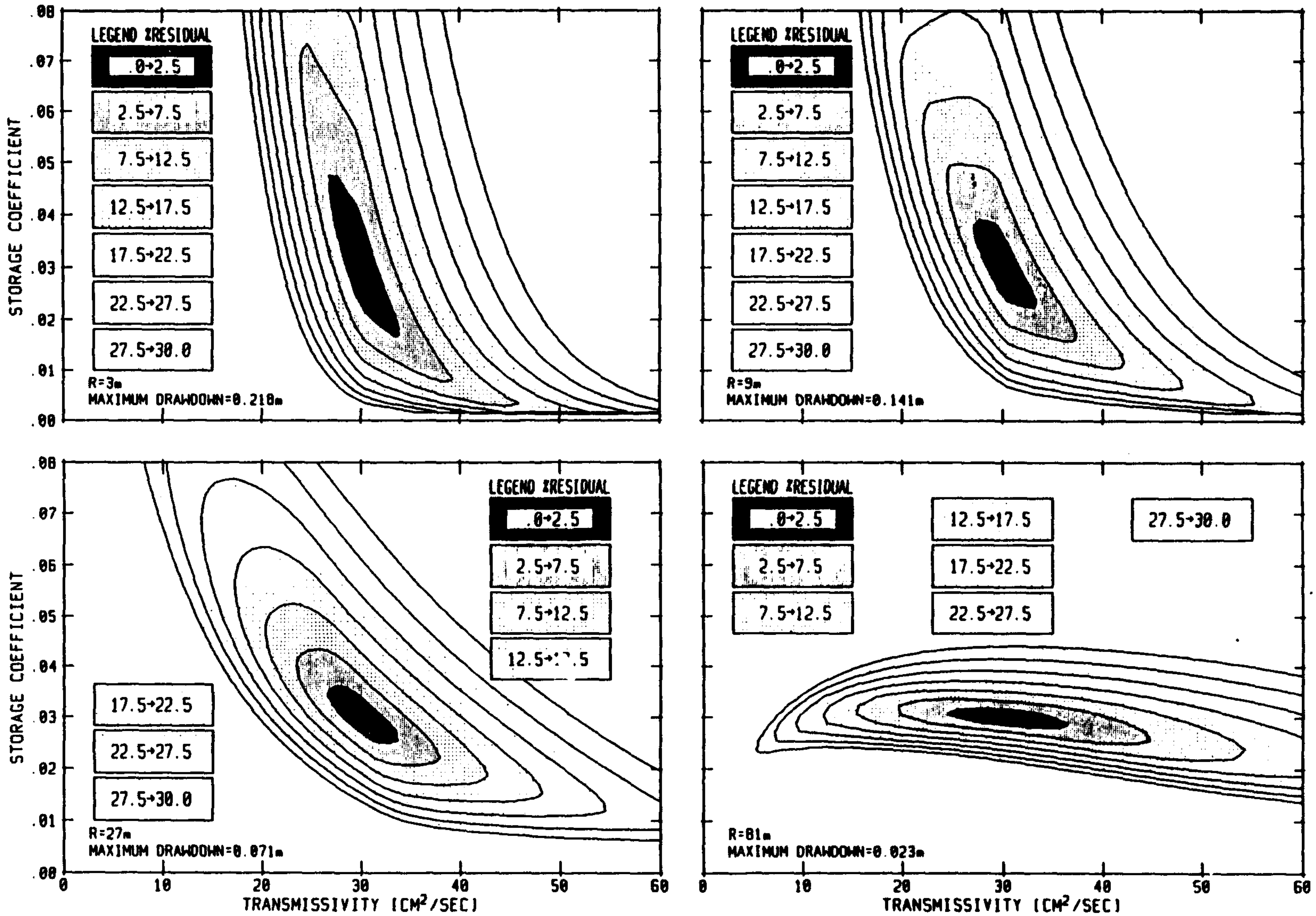


Figure 14. WELTEST Maps of the Cumulative Residual (as a Percentage) for an Aquifer Test With Pumpage at Regulated Intervals in an Idealized Homogeneous Aquifer With a Transmissivity and a Storage Coefficient of 30 cm^2/s and 0.03, Respectively.

435,587 seconds (5.04 days) continuously except during a 6,075-second (1.69-hour) power outage that began 55,820 seconds (15.5 hours) into the test. Problems were encountered with the flowmeter totalizer preventing an accurate record of discharge from the pump. Occasional measurements of the discharge rate were taken with a stopwatch and a calibrated 23.2-liter bucket. Table 11 lists the measurements of the discharge rate.

TABLE 11. MEASUREMENTS OF THE DISCHARGE RATE FOR AQUIFER TEST 1

DATE	TIME	CUMULATIVE SECONDS	FLOW (L/min)
5/18/89	8:00	---	69.64
5/18/89	13:00	18,000	69.64
5/18/89	16:15	29,700	69.64
5/19/89	7:35	84,900	68.51
5/19/89	16:25	116,700	68.51
5/22/89	12:35	362,100	69.64
5/23/89	6:10	425,400	67.75

Drawdown measurements were made in all the wells with an electric tape during the pumping period. During the first several hours of pumping, the wells near the pumping well were intensively monitored. Approximately 4 hours into the test, the first set of measurements at all 37 wells was made. Subsequent surveys were made periodically throughout the test with at least one survey each day. During the test, measurements were taken at 8 wells located several hundred meters away from the site in order to record the fluctuations in the water table caused by natural phenomena.

A total of 10 pressure transducers were used for the aquifer tests in order to get continuous drawdown measurements. These transducers were placed into Wells 2, 4, 6, 5, 8, 15, 17, 18, 25, and 30. For the first 3 hours of the aquifer tests, transducer measurements were recorded every 2 seconds. Thereafter, measurements were recorded every 2 minutes until the pumping stopped. At the end of the pumping, measurements of the water table recovery were taken every 2 seconds for approximately 3 hours, after which measurements were taken every 2 minutes.

Figure 15 shows contours of the cone-of-depression at elapsed times of 15,500 seconds (0.18 days); 82,400 seconds (0.95 days); 169,200 seconds (1.96 days); and 432,000 seconds (5.0 days). Figure 16 shows a three-dimensional representation of the drawdowns at 432,000 seconds (5.0 days). Also, Figure 16 shows the relatively steep slope in the water table near the pumping well which cannot be easily shown in Figure 15. (The plots in Figures 15 and 16 were produced by the inverse-weighting option in the computer program SURFER (Golden, 1990)). Figure 15 shows that at early times the drawdown cone is extended more in the westernly than the easternly direction; at late times the drawdown cone is extended more in the easternly direction than the westernly direction; the contours are very asymmetric; and the dimensions of the cone-of-depression change very little between 169,200 seconds and 432,000 seconds.

One explanation for the trends presented in Figure 15 is that the western region has a higher diffusivity than the eastern region. In such a situation, the aquifer would have an asymmetrical response to the pumping well. At the early times, the cone-of-depression would penetrate farther into the western region than the eastern region. At intermediate times, the pressure gradients in the western region would approach some type of quasi-steady-state while the pressure gradients in the eastern region continue to increase. At late times, the pressure gradient in both the eastern and western regions would reach a quasi-steady-state but the gradients would differ. Because of its lower diffusivity, the cone-of-depression would extend farther into the eastern region.

Figure 15 indicates that quasi-steady-state conditions over the total well network occurs around 169,200 seconds. After 169,200 seconds, the cone-of-depression is expanded slowly enough that the plots do not show the changes in the cone-of-depression. In both the eastern and western regions, considerable asymmetry and differences in the horizontal hydraulic gradients exist. These variations are most likely caused by heterogeneity in the aquifer's hydraulic conductivity field.

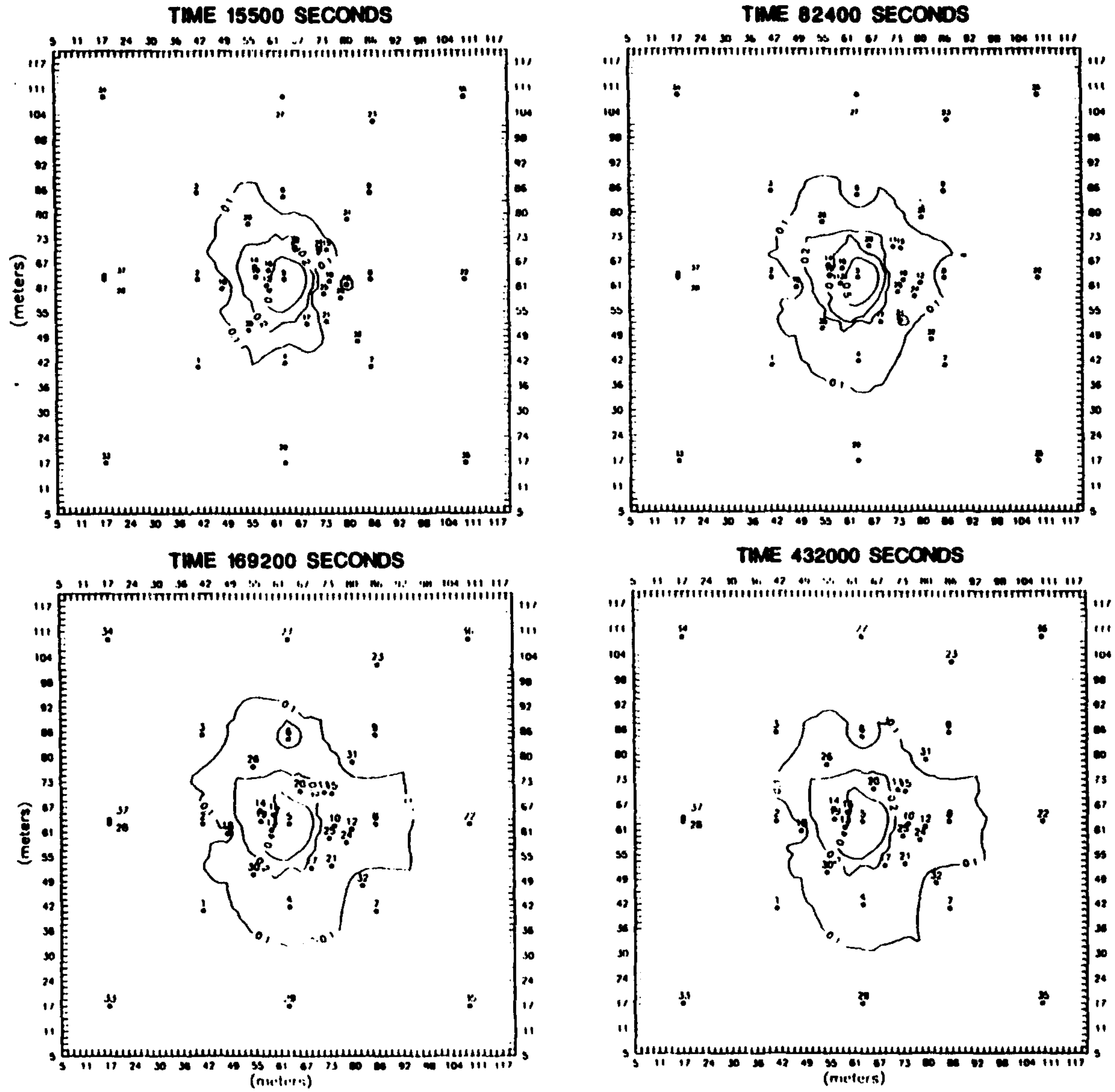


Figure 15. The Cone-of-Depression for Aquifer Test 1 at Different Times.

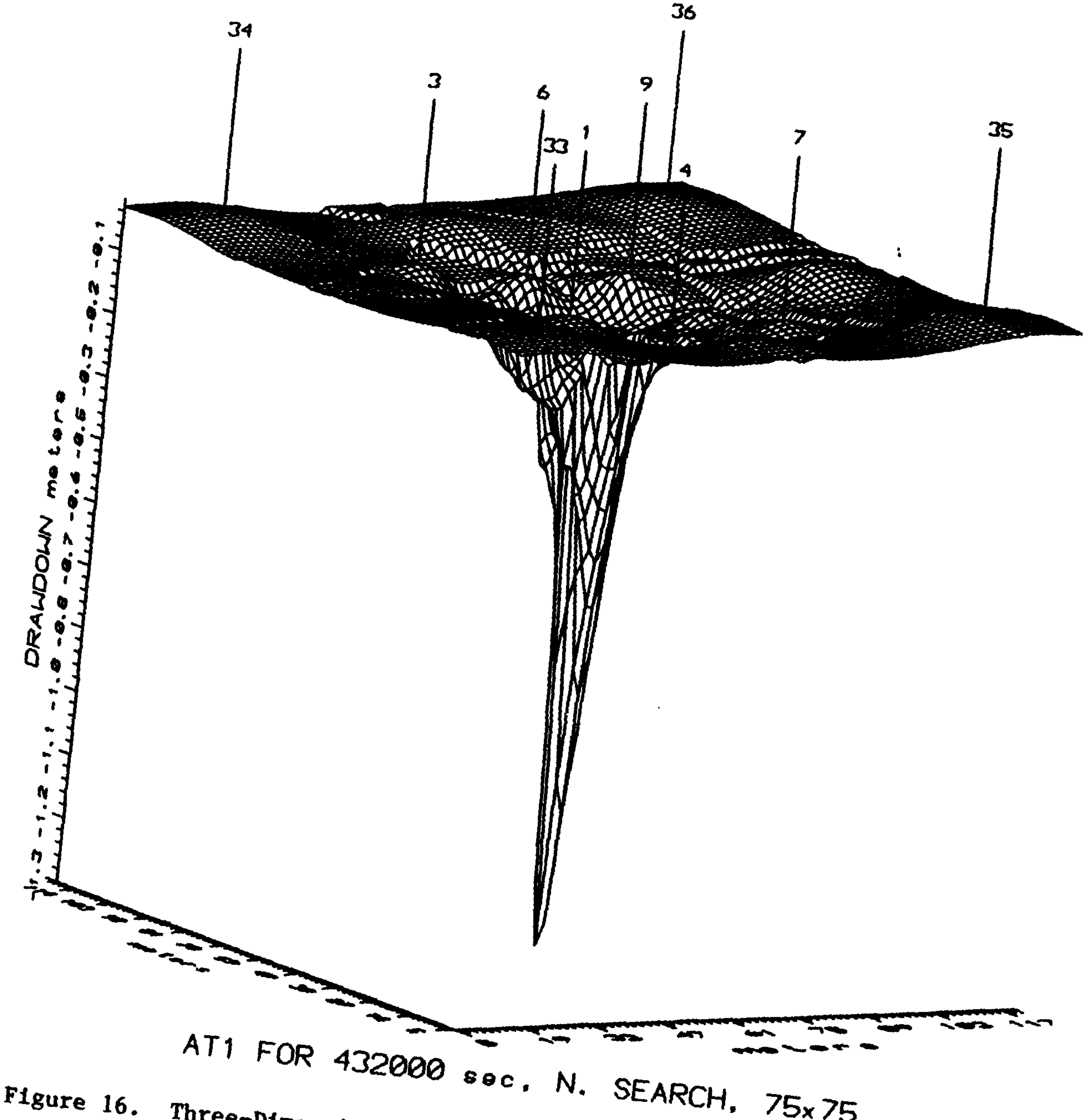


Figure 16. Three-Dimensional Map of the Aquifer Test 1 Final Drawdowns.

2. Transmissivities and Storage Coefficients From Program WELTEST

The WELTEST program was used to determine the values for transmissivity and storage coefficient at the location of the nine observation wells with transducers. Input to WELTEST included a pumping rate of 69.6 L/min before the power outage, a pumping rate of 68.5 L/min after the power outage, a saturated thickness of 7 meters, and an unconfined aquifer. WELTEST was applied to drawdown values collected during the first 10,000; 50,000; and 100,000 seconds.

A comparison between the predicted and the observed drawdown curves for the nine wells for the three time periods is shown in Figures 17, 18, and 19. In Figures 17, 18, and 19, one should note that the curve for each time period has been extrapolated to the end of the test to predict the final drawdowns.

Two trends should be noted in the figures. One trend is that the plotted data is nearly a straight line shortly after the pumping started and until the pump outage. This trend was present in almost all of the drawdown data taken manually at the 37 wells with electric tape. As a result, the Cooper-Jacob straight-line analysis could be easily applied to the data sets. The other trend is that after 100,000 seconds, most of the drawdown curves flatten out and/or exhibit large fluctuation about a mean value.

An explanation for the trend in the data points after 100,000 seconds has not been sought by the author. Possible explanations include a region of high hydraulic conductivity near the boundary of the well network or delayed drainage from low permeability sediments within the well network. An investigation into the reason for the trend would include using image wells in WELTEST and/or three-dimensional groundwater flow models. Such an investigation may lead to some interesting hypotheses, but it would be very time consuming and would not lead to any changes in the calculated values of transmissivities. As a result, such an investigation was not pursued.

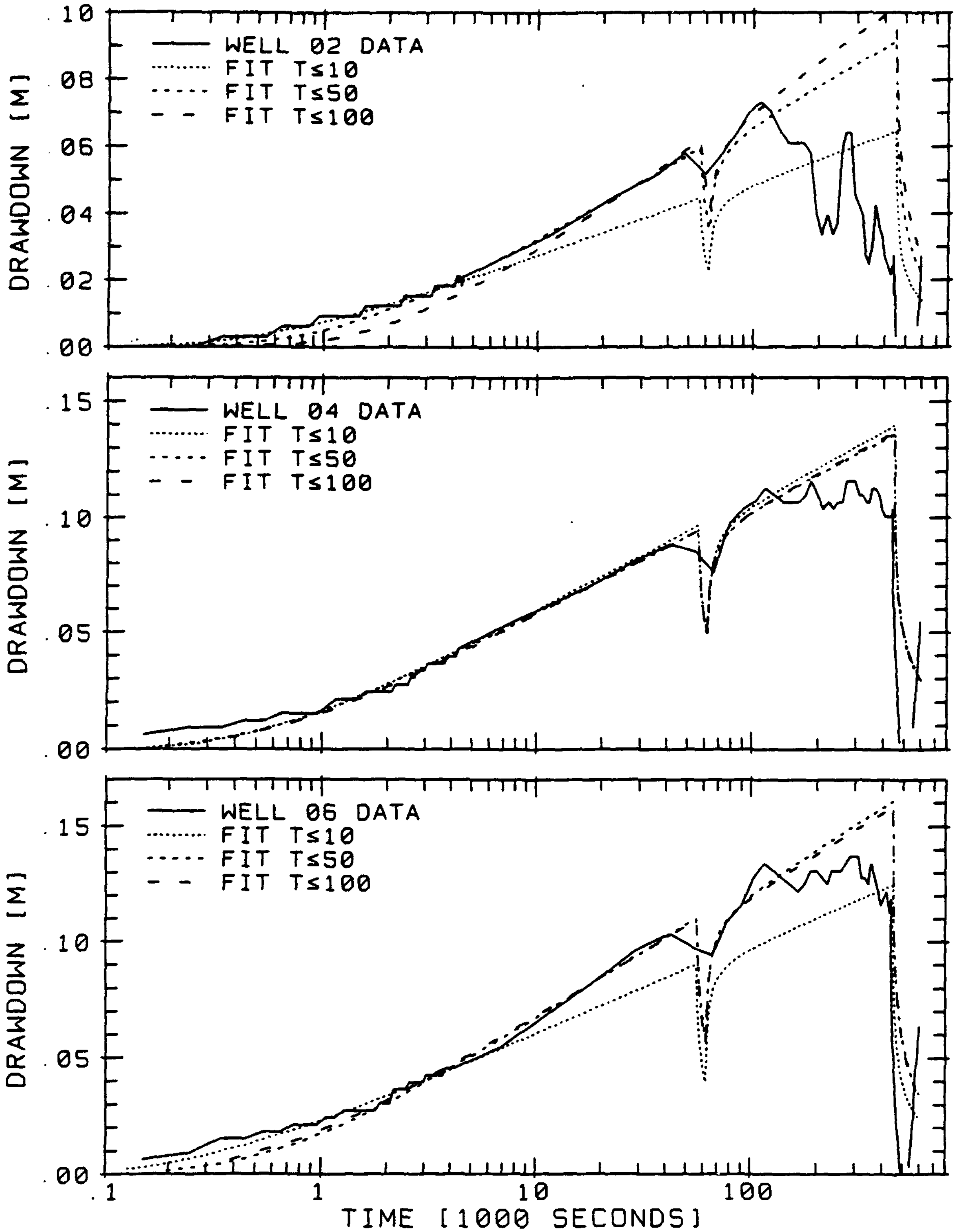


Figure 17. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 2, 4, and 6.

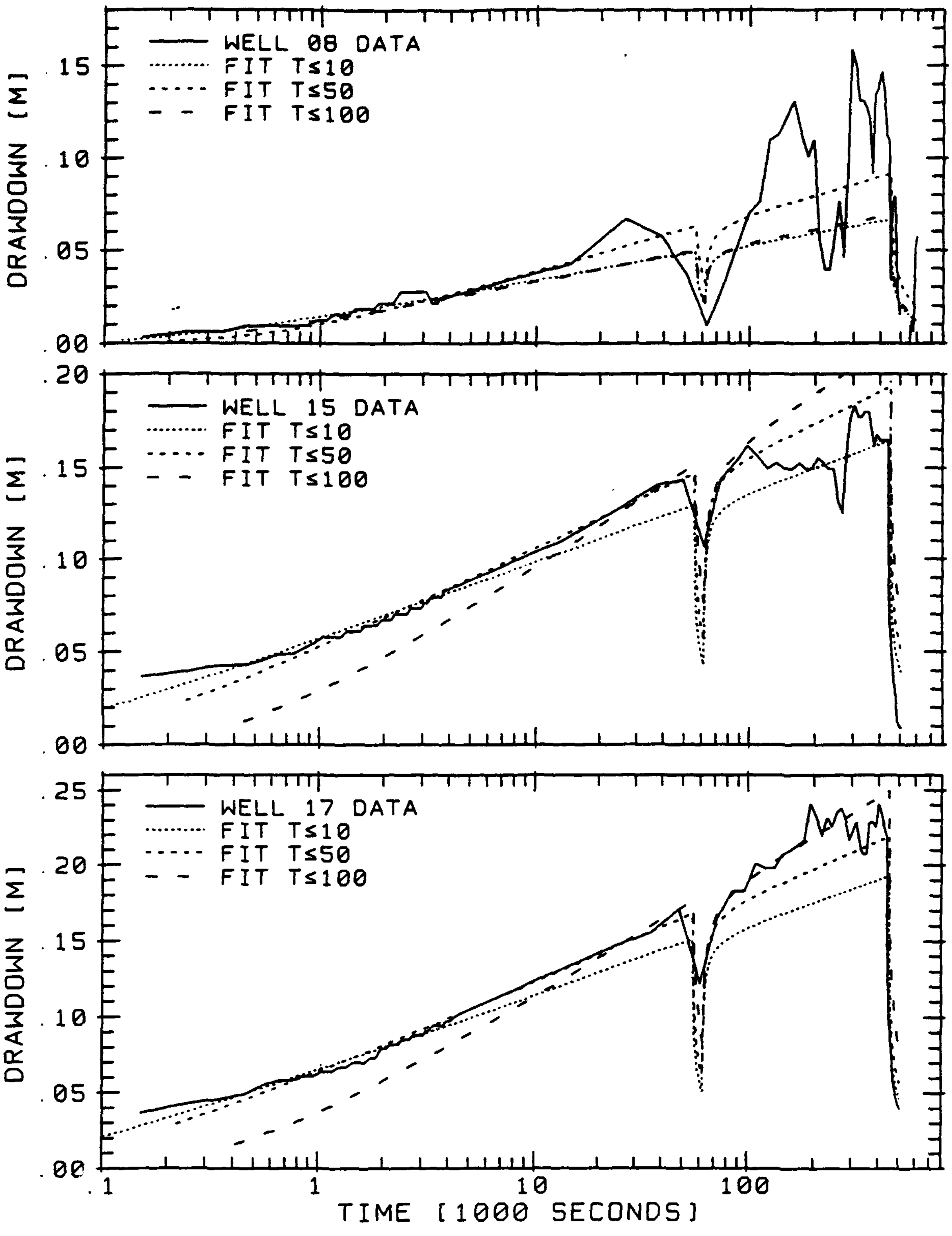


Figure 18. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 8, 15, and 17.

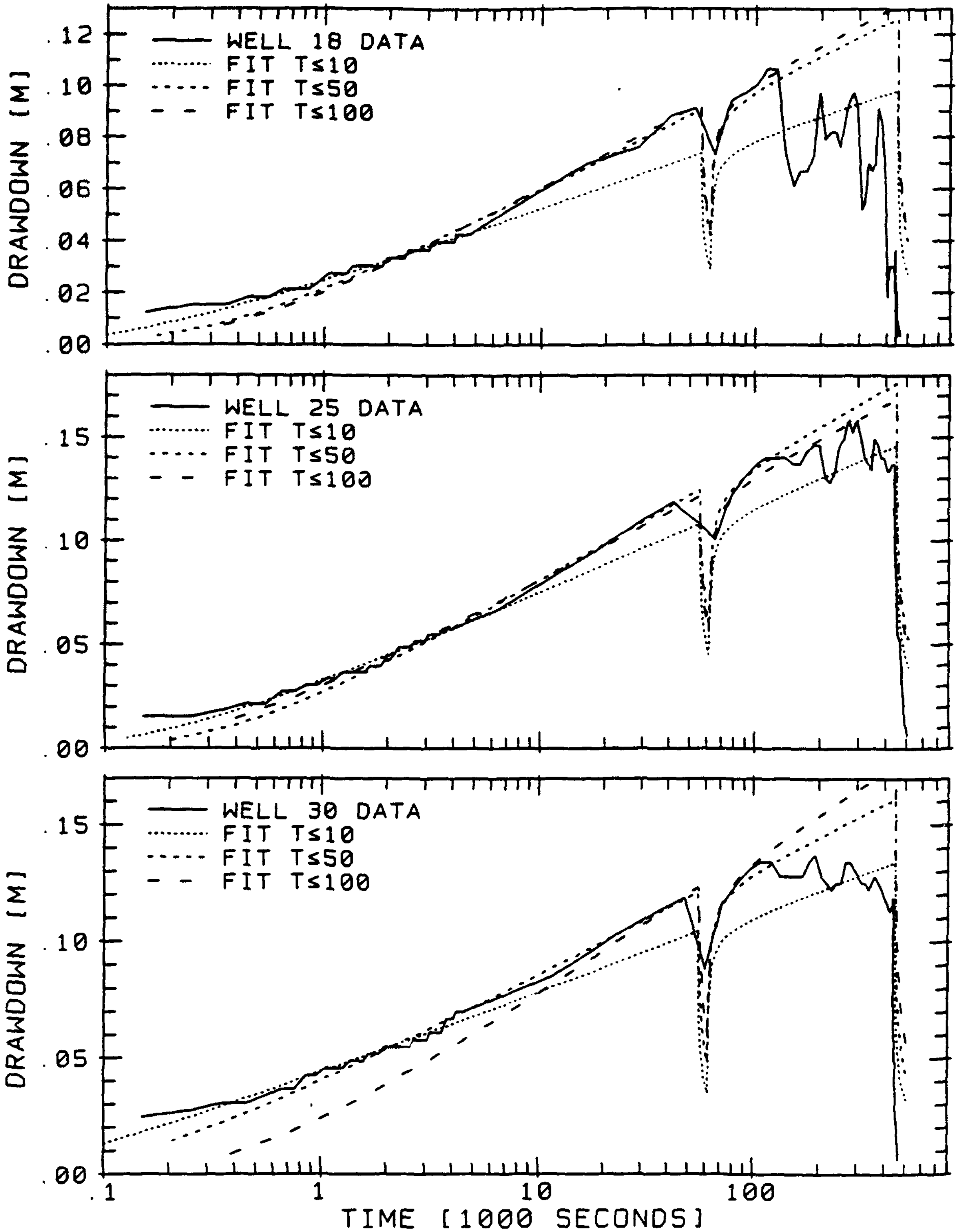


Figure 19. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 18, 25, and 30.

Table 12 lists the combination of transmissivity and storage coefficient values that provided the time-drawdown curve that best fit the observed time-drawdown curve as determined by the program WELTEST. Included in Table 12 are the factors by which the best value for either the transmissivity and the storage coefficient values can be multiplied or divided by so that the calculated residual is increased to 0.10 and to 0.20. These adjustment factors are a measure of the sensitivity of the final answer to both transmissivity and the storage coefficient. Table 12 shows that the match between the observed and the predicted time-drawdown curves is more sensitive to the storage coefficient than to the transmissivity. No values are listed for a residual interval when the "best" set of transmissivity and storage coefficient values lead to a residual that is greater than the designated residual. No results are provided for Well 8 at 100,000 seconds because no set of transmissivity and storage coefficient values could produce a residual less than 20 percent.

Table 12 shows that as the time period increases, the range in the calculated variables decreases. For the 10,000-second period, the transmissivities vary from 40 to 100 cm^2/s and the storage coefficients from .002 to .03. For the 100,000 second period, the transmissivities vary from 30 to 50 cm^2/s and the storage coefficients from .01 to .05. This trend is expected, because as time increases equilibration processes in the aquifer (e.g., crossflows) will result in symmetry and smoothness in the hydraulic pressure field.

Table 12 shows that the average value of the transmissivities decreases over time, whereas the average value of the storage coefficients increases over time. The average transmissivity (excluding Well 8) for times 10,000; 50,000; and 100,000 seconds is 59, 43, and 38 cm^2/s, respectively. The average storage coefficients (excluding Well 8) for times 10,000; 50,000; and 100,000 seconds is 0.011, 0.016, and 0.022, respectively. The trends in the transmissivities and storage coefficients are related to stress responses of the aquifer system.

TABLE 12. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 1 AT 10,000; 50,000; AND 100,000 SECONDS

Well	Time (seconds)	Transmissivity Value	Transmissivity 10%	Transmissivity 20%	Storage Coefficient Value	Storage Coefficient 10%	Storage Coefficient 20%
2	10K	92.90	*/1.20	*/1.58	.02818	*/1.17	*/1.38
4	10K	42.46	*/1.17	*/1.48	.01413	*/1.15	*/1.41
6	10K	53.46	*/1.17	*/1.41	.00832	*/1.26	*/1.58
8	10K	104.24	*/1.05	*/1.38	.01072	*/1.10	*/1.62
15	10K	52.24	*/1.12	*/1.32	.00282	*/1.45	*/2.14
17	10K	43.45	*/1.15	*/1.32	.00295	*/1.45	*/2.09
18	10K	73.79	*/1.15	*/1.35	.00955	*/1.32	*/1.82
25	10K	48.75	*/1.15	*/1.38	.01862	*/1.29	*/1.66
30	10K	61.38	*/1.15	*/1.32	.00302	*/1.41	*/2.04
2	50K	57.28	*/1.15	*/1.41	.03802	*/1.23	*/1.55
4	50K	44.46	*/1.15	*/1.38	.01413	*/1.29	*/1.66
6	50K	36.98	*/1.12	*/1.35	.01349	*/1.26	*/1.66
8	50K	64.27	NC	*/1.35	.02089	NC	*/1.58
15	50K	39.63	*/1.12	*/1.29	.00575	*/1.48	*/2.24
17	50K	36.14	*/1.12	*/1.29	.00447	*/1.51	*/2.34
18	50K	51.05	*/1.12	*/1.32	.01660	*/1.32	*/1.78
25	50K	36.14	*/1.15	*/1.35	.03020	*/1.32	*/1.78
30	50K	45.50	*/1.12	*/1.29	.00603	*/1.45	*/2.14
2	100K	46.56	*/1.10	*/1.29	.05623	*/1.23	*/1.66
4	100K	43.45	*/1.15	*/1.32	.01514	*/1.35	*/1.91
6	100K	37.85	*/1.15	*/1.32	.01230	*/1.35	*/1.91
8	100K	-	NC	NC	-	NC	NC
15	100K	28.71	NC	*/1.23	.01995	NC	*/1.95
17	100K	25.59	*/1.02	*/1.26	.01698	*/1.17	*/2.04
18	100K	48.75	*/1.12	*/1.32	.01862	*/1.38	*/2.00
25	100K	39.63	*/1.15	*/1.32	.02512	*/1.45	*/2.14
30	100K	35.32	*/1.02	*/1.26	.01698	*/1.20	*/2.00

*K = 1,000
NC = not calculated
*/ = multiplied or divided by

Note: The pumped well, Well 5, is not listed because of the large uncertainty associated with determining its effective well radius (i.e., the distance from the point of pumping to the point of observation).

As previously mentioned, when an aquifer is stressed, the initial pressure response is first transmitted into and through the zones of high diffusivities. At early times, hydraulic pressure in the well will better represent the pressure in zones of high diffusivities rather than the averaged pressure in the aquifer at the well. Consequently, an analysis of the well data at early times will lead to estimates of storage

coefficients and transmissivities more representative of the zones of high diffusivities rather than of the total thickness of the aquifer.

Because the pressure gradients between the zones of high and low diffusivity dissipate over time, hydraulic pressure in the well will, at late times, better represent pressure in the total aquifer rather than in zones of high diffusivities. Consequently, an analysis of the well data at late times will lead to estimates of transmissivities and storage coefficients more representative of the total aquifer than the zones of high diffusivities.

3. Transmissivities by the Cooper-Jacob Straight-Line Method

As discussed in Section IV B, the Cooper-Jacob analysis at large dimensionless time is preferred over the Theis curve fitting technique in determining values of transmissivities for a distributed-parameter model. As such, the Cooper-Jacob analysis is used below to determine the average transmissivity value of the aquifer. Based on Figure 15, the influence of the pumping well was only sufficiently large enough at the 28 wells in the interior of the well network to cause the drawdown necessary to perform a reliable Cooper-Jacob analysis.

Recalling from Section IV C, the Cooper-Jacob approximation should be applied only when u is equal to or less than 0.07. Using the range of parameters estimated from the Theis curve fitting analysis, it appears that the Cooper-Jacob analysis is appropriate 3 to 4 hours after pumping begins. All that is required to determine the transmissivity from Equation (12) is the slope of the drawdown curves from semilogarithmic plots.

Examination of these drawdown plots for the 27 wells confirms the trends observed in Figures 17-19: (1) an approximate straight-line after 1 hour of pumping; and (2) a change in the slope of the line at about 1 day. Because of the concern of the pump outage at 15 hours and possible boundary effects at 1 day, the straight-line analyses were done cautiously. All of the slopes for wells near the pumping well were

calculated from times less than 15 hours; and all the slopes for the wells far from the pumping well were calculated for times less than 1 day.

Calculations of the slopes were done with the aid of a computer program. This program graphically displays drawdown data and permits the marking of any segment of the curve with cross-hairs. The best fit straight-line can be calculated by a linear regression through the data points in the designated segment or by the slope between designated endpoints of the segment. At wells where transmissivities were calculated using both transducer and manual measurements, the transducer-based transmissivity estimate was considered more accurate. Table 13 lists the transmissivities calculated by the Cooper-Jacob straight-line method.

TABLE 13. TRANSMISSIVITIES CALCULATED BY THE COOPER-JACOB STRAIGHT-LINE METHOD FOR AQUIFER TEST 1

Well	T (cm^2/s)	Well	T (cm^2/s)	Well	T (cm^2/s)	Well	T (cm^2/s)
1	57	10	36	19	34	28	-
2	50	11	38	20	38	29	-
3	56	12	29	21	40	30	43
4	40	13	33	22	-	31	34
5	34	14	36	23	-	32	35
6	49	15	29	24	38	33	-
7	42	16	27	25	37	34	-
8	27	17	31	26	36	35	-
9	35	18	46	27	-	36	-

The arithmetic and geometric means for the 27 transmissivity values in Table 13 are 38 and 37 cm^2/s, respectively. The standard deviation for the transmissivities is 8.2 cm^2/s and all except two of the transmissivities are within 35 percent of the arithmetic average. Within the transmissivity field, there appears a region of high transmissivity apparent in the west and northwest (Wells 1, 2, 3, 6, 18, 30) and a region of low transmissivity in the east (Wells 8, 12, 15).

E. AQUIFER TEST 2

1. Test Description

Aquifer Test 2 included cyclic pumping at Well 5 and measuring drawdowns at the wells with pressure transducers. Cyclic pumping began on 1 June 1989, and ended on 6 June 1989. The targeted average pumping rate was 68 L/min (constant pumping rate for Aquifer Test 1). The average pumping rate was achieved by a series of pulses. A pulse included a period when the pumping rate was approximately 120 L/min and a period when the pump rate was zero L/min. During the first 5 days of testing, a pulse included 4 hours pumping and 3 hours no pumping. The last 2 days of testing, a pulse included 2 hours pumping and 1-1/2 hours no pumping.

Immediately after the pump was turned on or turned off, the water level changed quickly in the observation wells. The relatively quick rate of change in water levels was measured by pressure transducers. Data was collected every 8 seconds throughout the duration of the test. Because of the limited number of transducers, the transducers were moved from well to well during the test. At the end of Pulse 7, 12 transducers were moved to new wells. At the end of Pulse 14, 3 of the 13 transducers were moved to new wells. The relocation of transducers permitted data to be collected at all 28 wells within the interior of the well network.

An electronic timing device automatically turned the pump on and off. This device increased the consistency of pulse cycles; eliminating the necessity of a night shift. Accurate measurements were made of the total discharge by a mechanical flowmeter (flowmeter calibration was checked at the Engineering Laboratory after the test and found to be within 1 percent). Measurements of the total amount of groundwater discharged were taken after Pulses 1, 3-10, 14, 15, and 19-21. Table 14 provides data on the actual pumping schedule and location of transducers during Aquifer Test 2. Table 12 shows that the pumping rate gradually declined over the duration of the test. During Pulse 7, the pump prematurely stopped 48 minutes after start-up because of a power outage.

TABLE 14. PUMPING SCHEDULE AND LOCATION OF TRANSDUCERFOR AQUIFER TEST 2

Pulses	Start/End (date, time)	Pulse On/ Pulse Off	Discharge Rates for Pulses (L/min)		Wells With Transducers
1 - 7	6/1/89 12:30:00	4 hours	1	(121.1)	2 4 5 6 8 14
	6/3/89 8:02:15	3 hours	2 & 3	(119.2)	15 17 19 20
			4 to 7	(117.3)	26 30
8 - 14	6/3/89 12:30:00	4 hours	8	(117.3)	1 5 9 10 11
	6/05/89 13:30:00	3 hours	9,10	(116.2)	12 16 18 21
			11 to 14	(115.4)	24 31 32
15 - 21	6/05/89 13:30:00	2 hours	15	(116.2)	3 5 7 11 10 12
	6/06/89 14:00:00	1.5 hours	16 to 21	(115.4)	13 16 18 21
					24 31 32

Note:
- The Cumulative Discharge reading was taken after Pulses 1, 3-10, 14, 15, and 19-21
- Pulse 7 consisted of 48 minutes on and 4 hours 28 minutes off

During the test, manual drawdown measurements were made in all of the wells with an electric tape. These data provided a means to verify the accuracy of the transducer measurements and determine the amount of offset to be added to the transducer measurements at the second and third group of wells. As done in Aquifer Test 1, drawdown measurements were also taken at eight wells that were located several hundred meters away from the site in order to estimate the naturally occurring fluctuations in the water table. All the analysis was performed on the experimental data after it had been detrended for these fluctuations.

2. Transmissivities and Storage Coefficients From Program WELTEST

The WELTEST program was used to determine the values of transmissivity and storage coefficient for each set of transducer measurements. The variable pumping rate listed in Table 14 was used to generate the drawdown curves. The data sets were divided into 3 groups. The groups are Pulses 1-7, Pulses 8-14, and Pulses 15-21. For each series of pulses at a well, the drawdown data were analyzed with respect to the first 3 pulses, the second 3 pulses, and the first 6 pulses. The multiple analyses were performed to better detect any trends in the data.

Potential sources for trends in drawdown data include the effects of far-field boundary conditions and cyclic fluctuation of the water table. Aquifer Test 1 revealed that boundary conditions near the test site affected drawdown at some of the wells 1 day after pumping. Given the same average pumping rate at Aquifer Test 1, the potential existed for boundary conditions to affect drawdown values after the third pulse.

Figures 20 through 25 show the match between the experimental data and the curves generated by WELTEST. Appendix A lists the calculated values of transmissivity and storage coefficients and their respective sensitivities at confidence limits of 10 percent and 20 percent. Several observations from the figures are listed in Table 15.

TABLE 15. OBSERVATIONS FROM THE EXPERIMENTAL AND WELTEST DRAWDOWN DATA SETS FROM AQUIFER TEST 2

1. Although 7 pulses exist in each figure, only 6 pulses are used in the data analyses. For each of the three curve fits, the predicted well response is made for all 7 pulses.

2. Most of the cumulative drawdown measurements are less than 0.20 meter; for ten of the plots the greatest measured drawdown is less than 0.1 meter.

3. The water level responds almost immediately after a change in the pumping schedule.

4. A spike (an unexpectedly large recovery) in the drawdown values occurred at Well 30 after the fourth pulse.

5. The cyclic response at Wells 8, 10, and 12 has considerably more scatter than the patterns for the other wells.

6. The WELTEST curve for the group of 6 pulses fits the experimental data acceptably for Pulses 1-7 and 15-20. For Pulses 8-14, the first 3 pulses match the WELTEST curves but the last 4 pulses do not. In general, the observed drawdown response to the last 4 pulses is less significant than one would expect from the WELTEST simulation. This trend is in harmony with the results in Figures 17-19.

Observation 1 is intended to clarify that the seventh pulse in each group of pulses was not used in the curve fitting procedure. Observations 2 and 3 demonstrate the necessity for reliable transducers and data logging equipment. Observation 4 relates to the diagnosis of

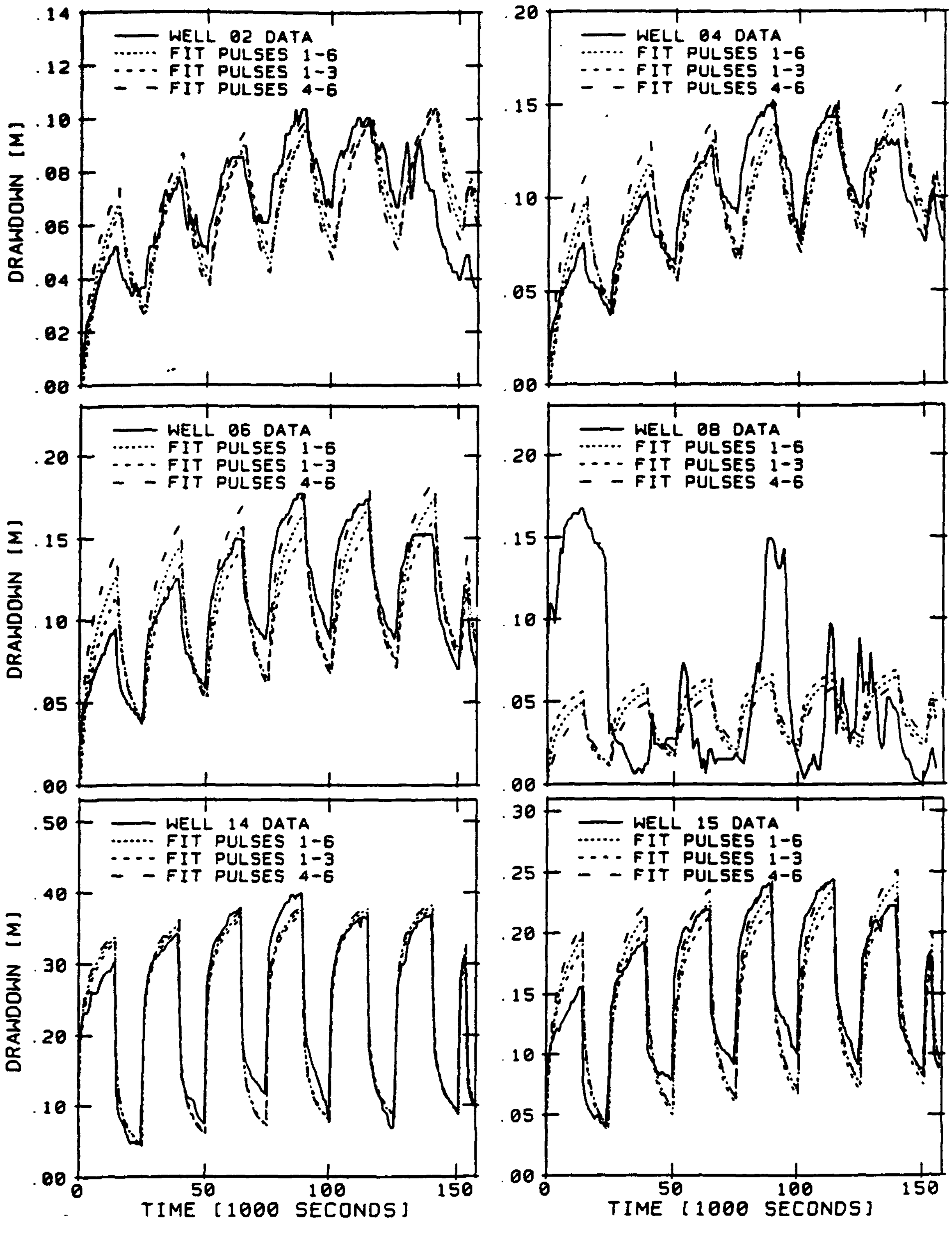


Figure 20. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 1 Through 7 at Wells 2, 4, 6, 8, 14, and 15.

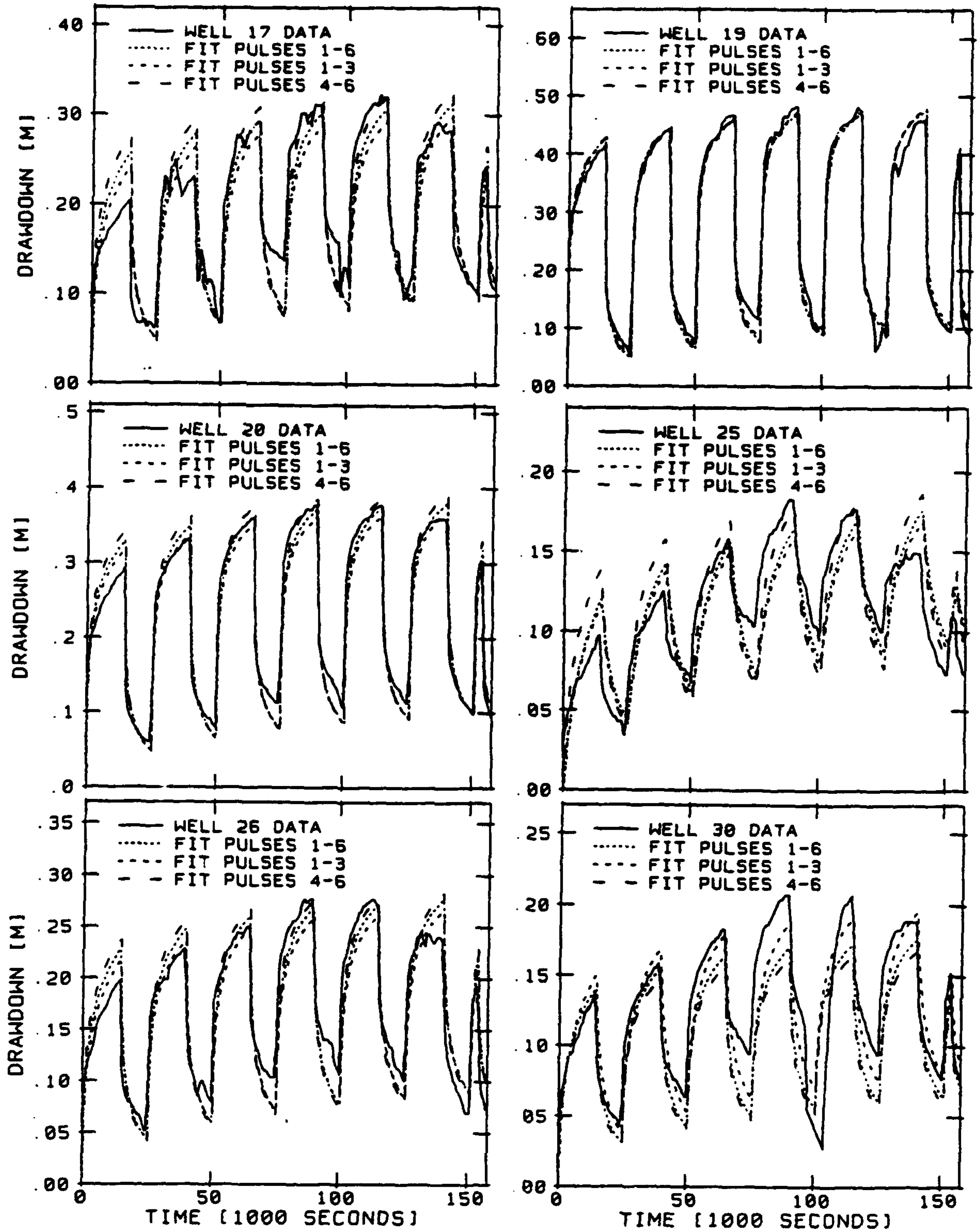


Figure 21. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 1 Through 7 at Wells 17, 19, 20, 25, 26, and 30.

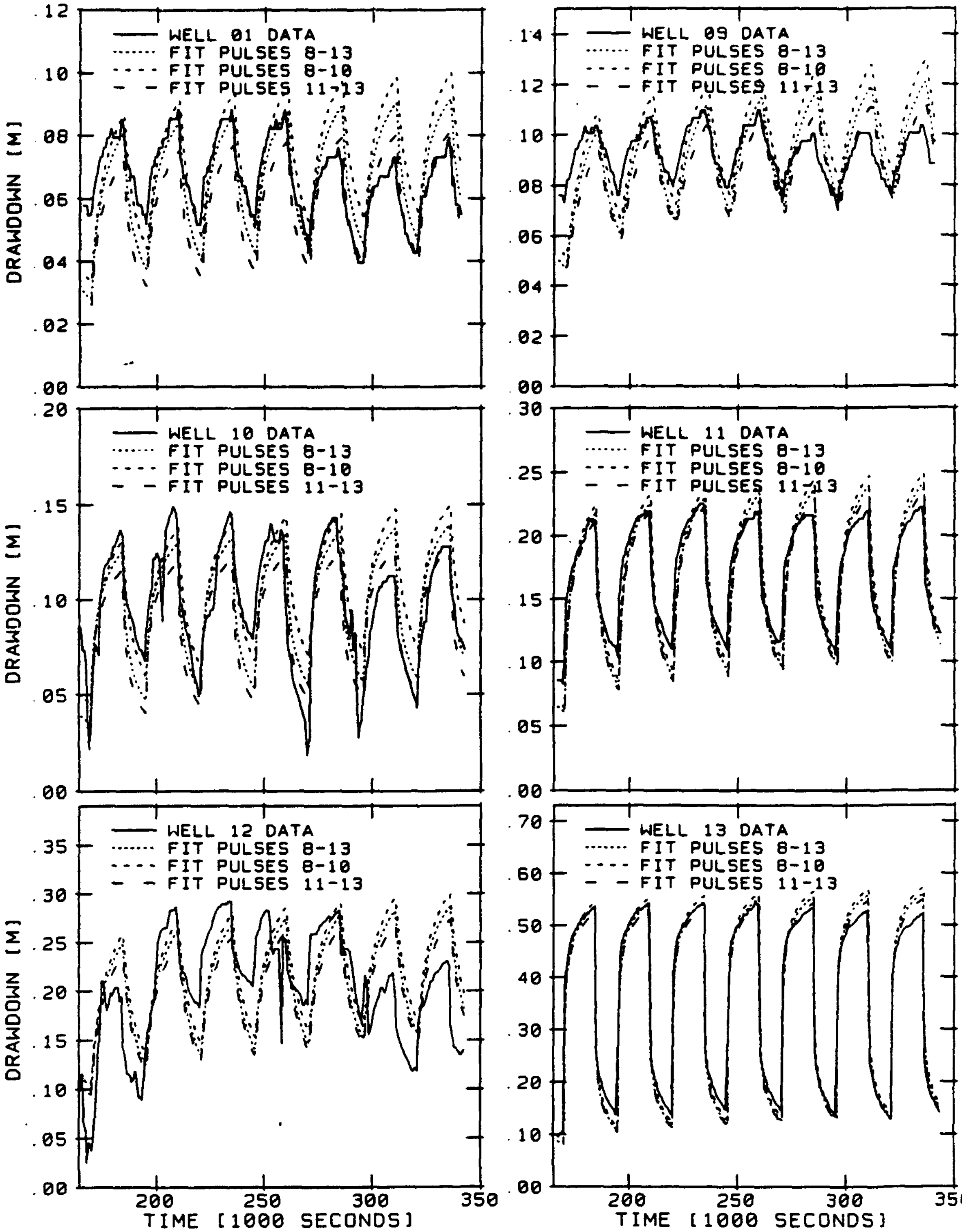


Figure 22. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 8 Through 14 at Wells 1, 9, 10, 11, 12, and 13.

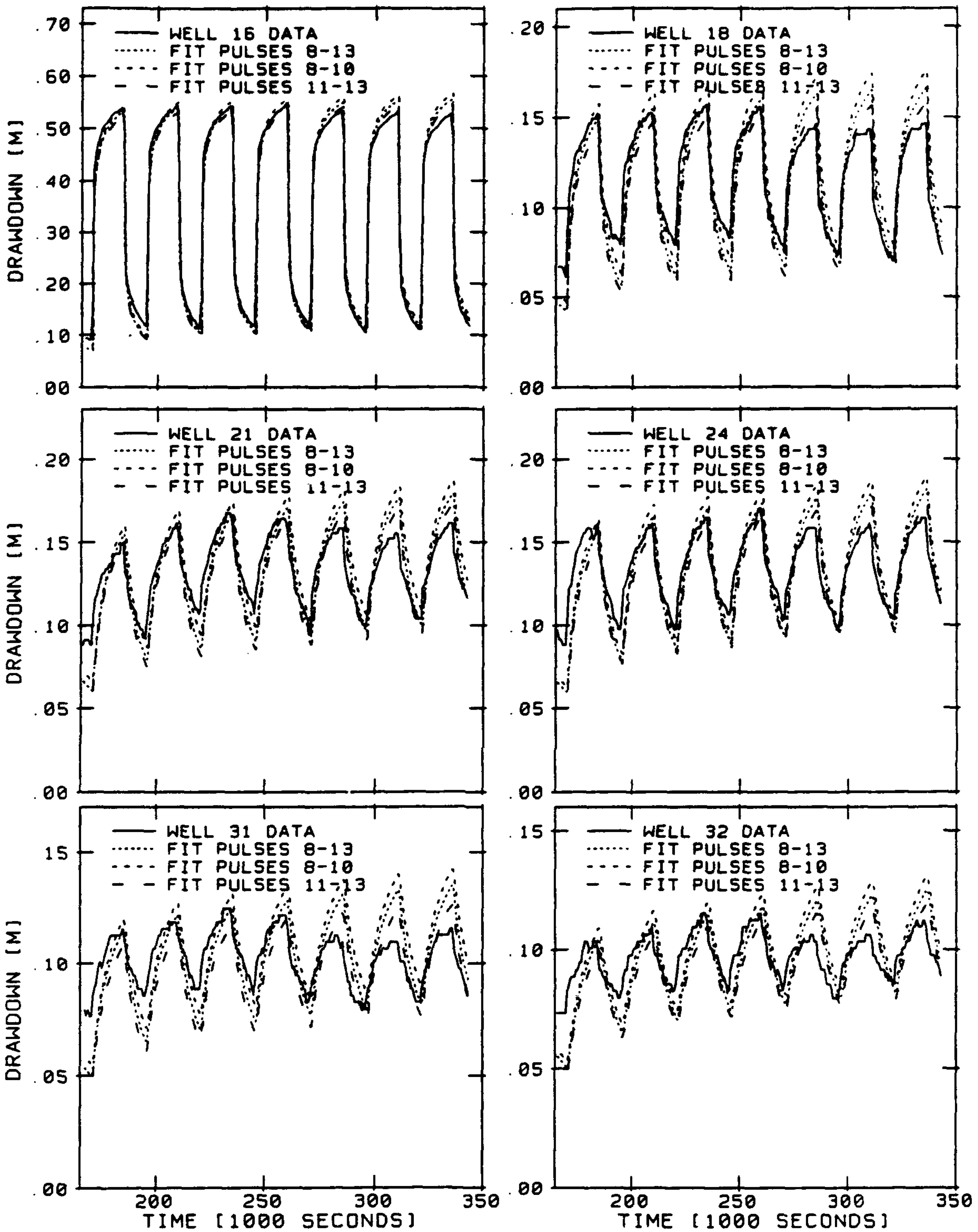


Figure 23. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 8 Through 14 at Wells 16, 18, 21, 24, 31, and 32.

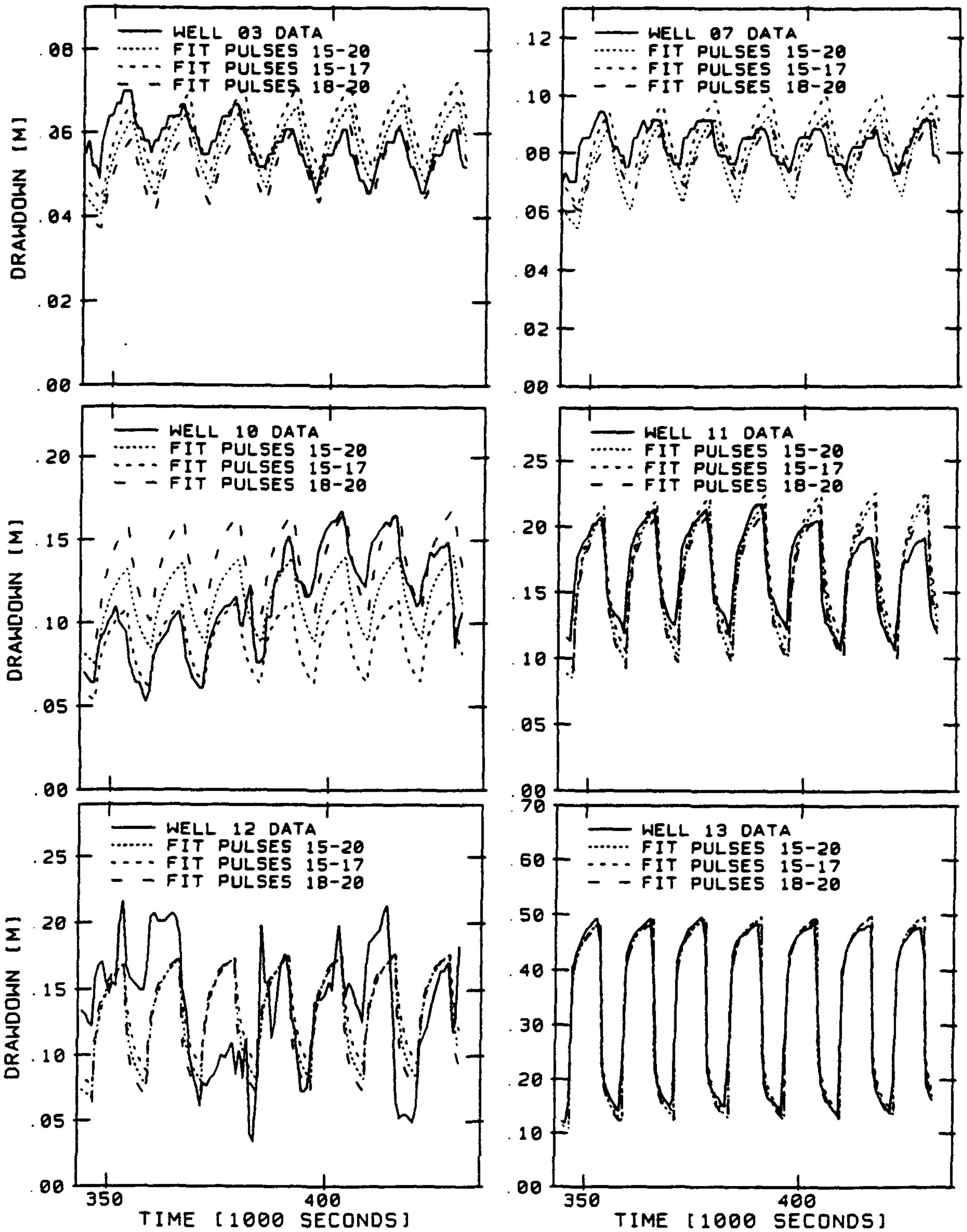


Figure 24. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 15 Through 21 at Wells 3, 7, 10, 11, 12, and 13.

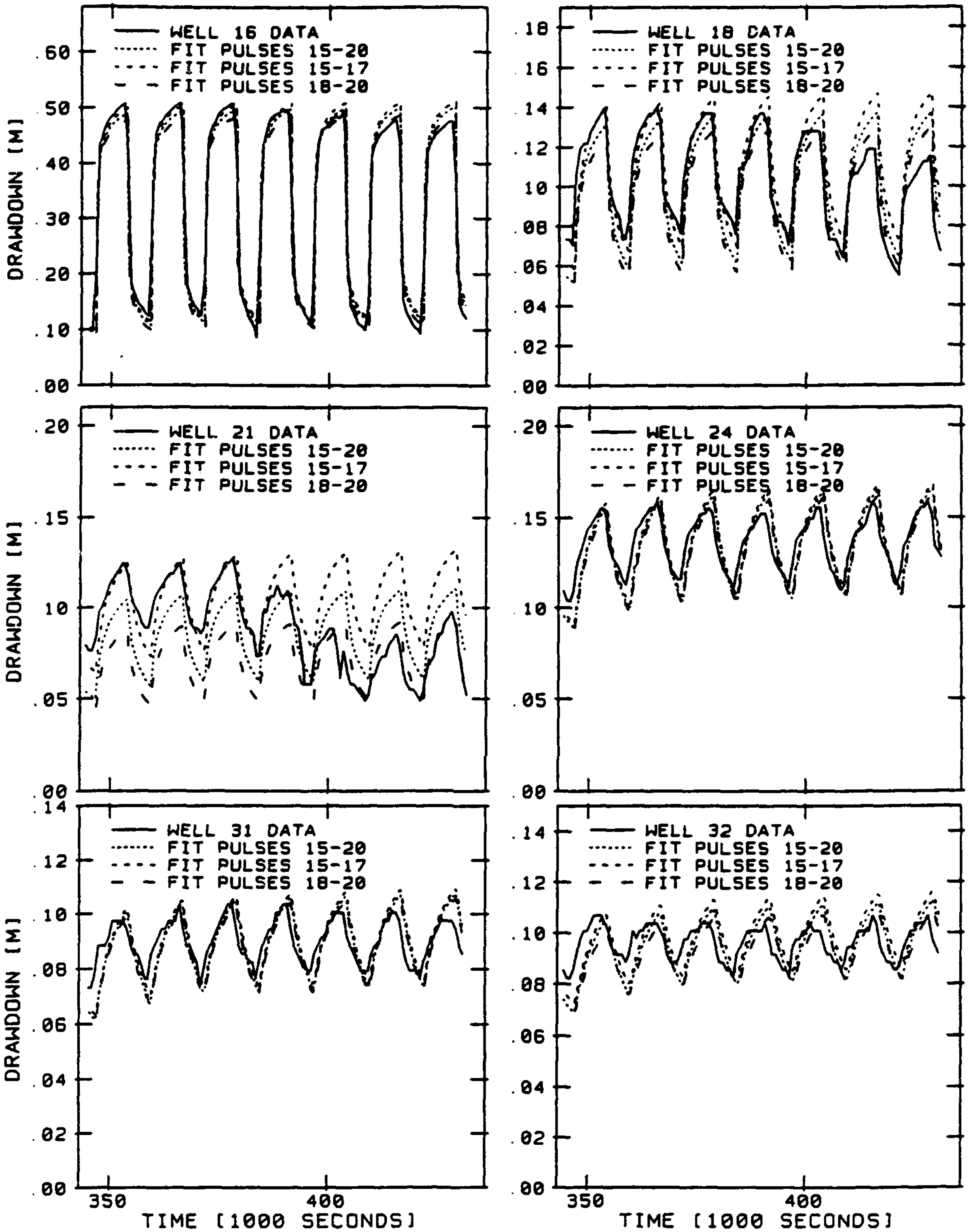


Figure 25. WELTEST Fits to Aquifer Test 2 Drawdowns for Pulses 15 Through 21 at Wells 16, 18, 21, 24, 31, and 32.

the spike after Pulse 4. The spike was caused by runoff from a rain event draining beneath faulty grout seals at Well 30. This discovery prompted regrouting at Well 30 before Aquifer Test 3. Observation 5 indicates that natural phenomena or anthropogenic effects in the vicinity of Wells 8, 10, and 12 may have led to the nonclassical behavior at each wells.

Observation 6 in Table 15 indicates that sometime between the the tenth and the eleventh pulse (3.1 days into the test), an altering of the response pattern in the aquifer was detected. The change may have been caused by the effects of boundary condition(s) or by the improper detrending of the experimental data. The latter reason, however, does not seem plausible because the amount of detrending adjustment between the tenth and the eleventh pulse is less than 0.002 m/day. The reason for the change in the well responses has not been investigated, but is speculated to be caused either by an area of high hydraulic conductivity near the boundaries of the well network or by a delayed drainage from low permeability materials within the boundaries of the well network.

Because of concern over the effects of boundary conditions after Pulse 11, none of the data after Pulse 11 is considered reliable. For the second set of pulses, only the hydraulic properties calculated for Pulses 8-10 are used. An examination of the data generated for Pulses 1-6 indicates a possible difference between Pulses 1-3 and Pulses 3-6. However, the importance of the trend does not seem significant because the transmissivities and storage coefficients calculated for Pulses 1-6 are typically within 10 percent of the values calculated for Pulses 1-3. Hence, the values calculated for Pulses 1-6 are used. Table 16 lists the values calculated by the program WELTEST for Aquifer Test 2.

The arithmetic and the geometric means for the 24 transmissivity values in Table 16 are 32 and 30 cm^2/s, respectively (within 27 percent of values from Test 1). In general, little variations exists among the different values; their standard deviation is 9.4 cm^2/s and all except 4 values are within 35 percent of the arithmetic average. The variations in the transmissivities indicate high values in the western region (at Wells 1, 2, and 18) and low values scattered through the well network (at Wells 8, 30, 12, 16, and 19).

TABLE 16. WELTEST CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 2

Well	T (cm^2/s)	S	Well	T (cm^2/s)	S
1	58.6	0.0214	15	32.2	.0123
2	42.5	0.0540	16	29.4	.000603
3	NC	NC	17	26.8	.00813
4	29.4	0.0407	18	43.5	.0200
5	NC	NC	19	25.0	.00257
6	32.2	0.0204	20	26.2	.00603
7	NC	NC	21	30.1	.0589
8	20.8	0.0141	24	32.2	.0457
9	37.9	0.0282	25	29.4	.0933
10	44.5	0.071	26	29.4	.0575
11	32.2	0.021	30	12.3	.0148
12	19.9	0.030	31	35.3	.0457
13	25.6	0.00178	32	36.1	.0490
14	27.4	0.00525			

NC = not calculated

The arithmetic value for the storage coefficients is 0.030. The values of storage coefficients have considerable variability and range over approximately two orders of magnitude. No clear trend seems to exist in the location of high storage coefficient values, but a trend exists with the low storage coefficient values. The lowest storage coefficient values (<0.01) are found near Well 5.

F. AQUIFER TEST 3

1. Test Description

Aquifer Test 3 included pumping Well 5 at a constant rate and measuring the drawdown in all 37 wells. The pumping began on 30 June 1989 at 0936 and ended on 7 July 1989 at 1614. The pump ran continuously for 628,473 seconds (7.27 days). A mechanical flowmeter was used to measure the cumulative discharge during the test (the flowmeter's calibration was checked at the Engineering Laboratory after the test and found to be within 1 percent). Based on the flowmeter's readings, the pumping rate declined from an initial rate of 121 L/min to a final rate of 110.5 L/min. Table 17 lists the history of the discharge rate.

TABLE 17. MEASUREMENTS OF THE DISCHARGE RATE FOR AQUIFER TEST 3

Date	Time	Cumulative Seconds	Average Discharge Rate (L/min)
6/30/89	9:36	16,080	121.1
6/30/89	14:04	95,940	121.1
7/1/89	12:15	197,220	117.0
7/2/89	16:23	280,380	113.6
7/3/89	15:29	364,620	111.7
7/4/89	14:53	397,440	110.9
7/5/89	12:55	443,940	110.9
7/6/89	14:38	536,520	110.5
7/7/89	10:31	608,100	110.5

Drawdown measurements were made in all wells with an electric tape during the pumping period. During the first several hours of pumping, the wells near the pumping well were intensively monitored. Approximately 5 hours into the test, the first set of measurements at all 37 wells were made. Subsequent surveys were made periodically throughout the test with at least one survey each day. During the test, measurements were taken at eight wells located several hundred meters away from the site to estimate the naturally occurring fluctuations in the water table.

A total of 13 pressure transducers were used for the aquifer tests in order to get continuous drawdown measurements. The transducers were placed into Wells 1, 2, 4, 5, 6, 8, 14, 17, 20, 25, 26, 30, and 31. For the first 3 hours of the aquifer tests, transducer measurements were recorded every 2 seconds. Thereafter measurements were recorded every 2 minutes until the pumping ceased. At the end of pumping, measurements of the water table recovery were taken every 2 seconds for approximately 3 hours, after which measurements were taken every 2 minutes.

Before the water table data was analyzed, the trend in the natural water table fluctuations was removed. As a check on the consistency between the transducer and the manual measurements, the two data sets were compared. The comparison showed good agreement between the data sets except for Well 6. At Well 6, the two data sets showed the same slope but the transducer data had values that were 0.06 meters

greater. The discrepancy is believed to have been caused by an incorrect initial manual measurement at Well 6.

Figure 26 shows contours for the cone-of-depression at elapsed times of 19,500 seconds (0.22 days); 95,000 seconds (1.1 days); 190,600 seconds (2.2 days); and 438,600 seconds (5.1 days). Figure 27 shows a three-dimensional representation of the drawdowns at 438,600 seconds. (The plots shown in Figures 26 and 27 were produced by the inverse-weighting option in the computer program SURFER (Golden, 1990)). This figure illustrates the relatively steep slope of the water table near the pumped well which Figure 26 does not adequately illustrate. Figure 27 shows: (1) at early times the cone-of-depression extends the farthest in the west and southwest regions; (2) at late times the cone-of-depression extends appreciably farther in the east than the west; (3) configuration of the cone-of-depression changes slightly between 190,600 and 438,600 seconds; (4) between time 190,600 and 438,600 seconds, the cone-of-depression has increased in the eastern region of the well network but decreased slightly in the western region.

The trend in the pressure gradients (Figure 26) agrees with the trends shown for Aquifer Test 1 (Figure 15). As previously mentioned, one interpretation of this trend is that zones of highest diffusivities exist in the western region. As in Figure 15, Figure 26 shows asymmetry in the contours that is due largely to heterogeneities in the aquifer. Unlike Figure 15, Figure 26 shows that at late times slight changes exist in the configurations of the cone-of-depression. One unexpected trend was the slight decrease in the drawdowns at Wells 1 and 3 between 190,600 and 438,600 seconds. An examination of all the drawdown data indicates that this trend is correct and is not a result of the mapping technique.

Several possible explanations exist for the slight decline in drawdowns at the western wells for late times. First, the decreases may have resulted from the gradual decrease in the pumping rate. However, the average pumping rate during this interval dropped only 3 percent. This change in pumping caused a 0.03-meter increase in the water table at the pumped well between 350,000 and 438,600 seconds. The predicted change at Wells 1 and 3 is negligible. Second, the decreases may have

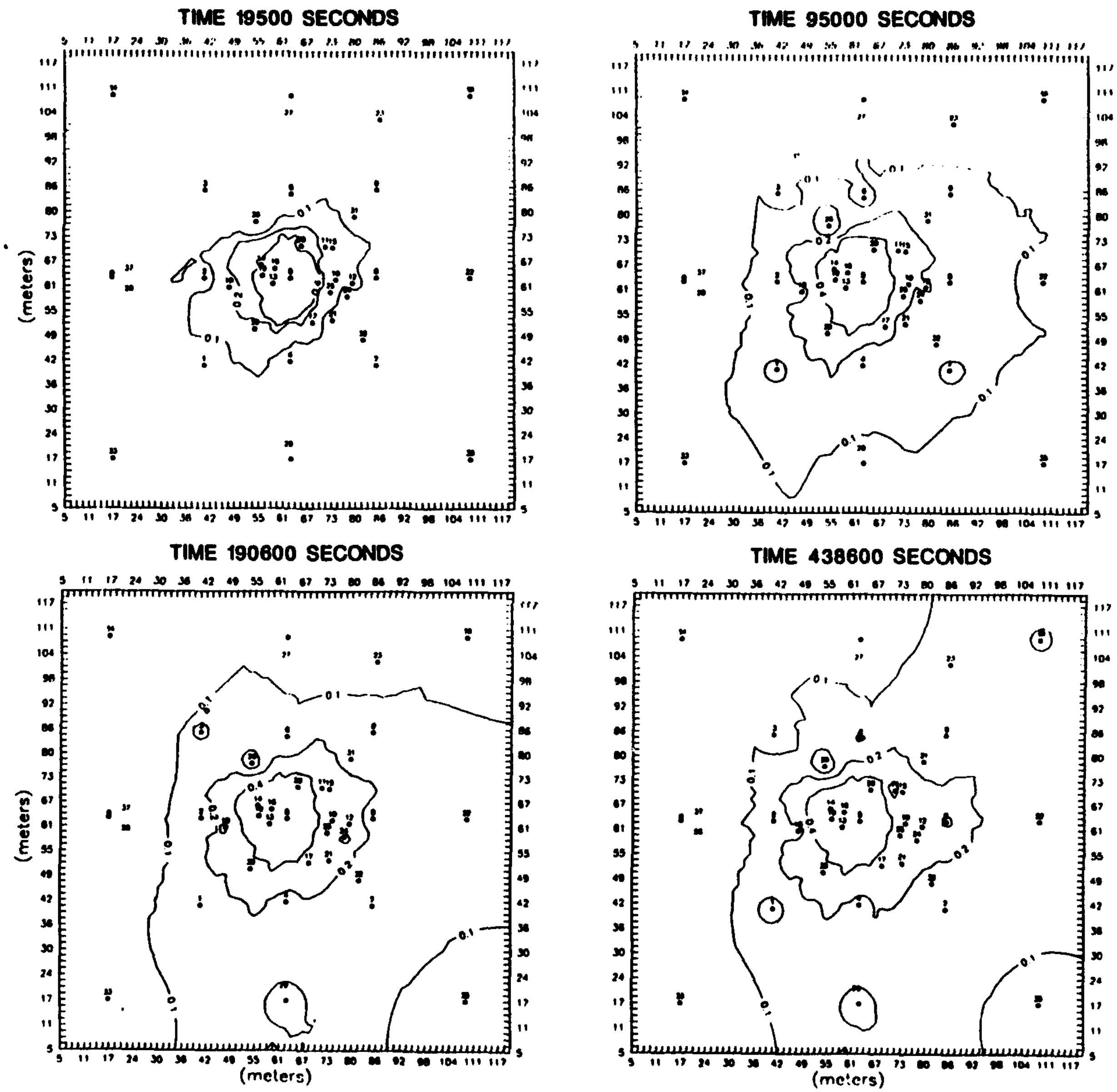


Figure 26. The Cone-of-Depression for Aquifer Test 3 at Different Times.

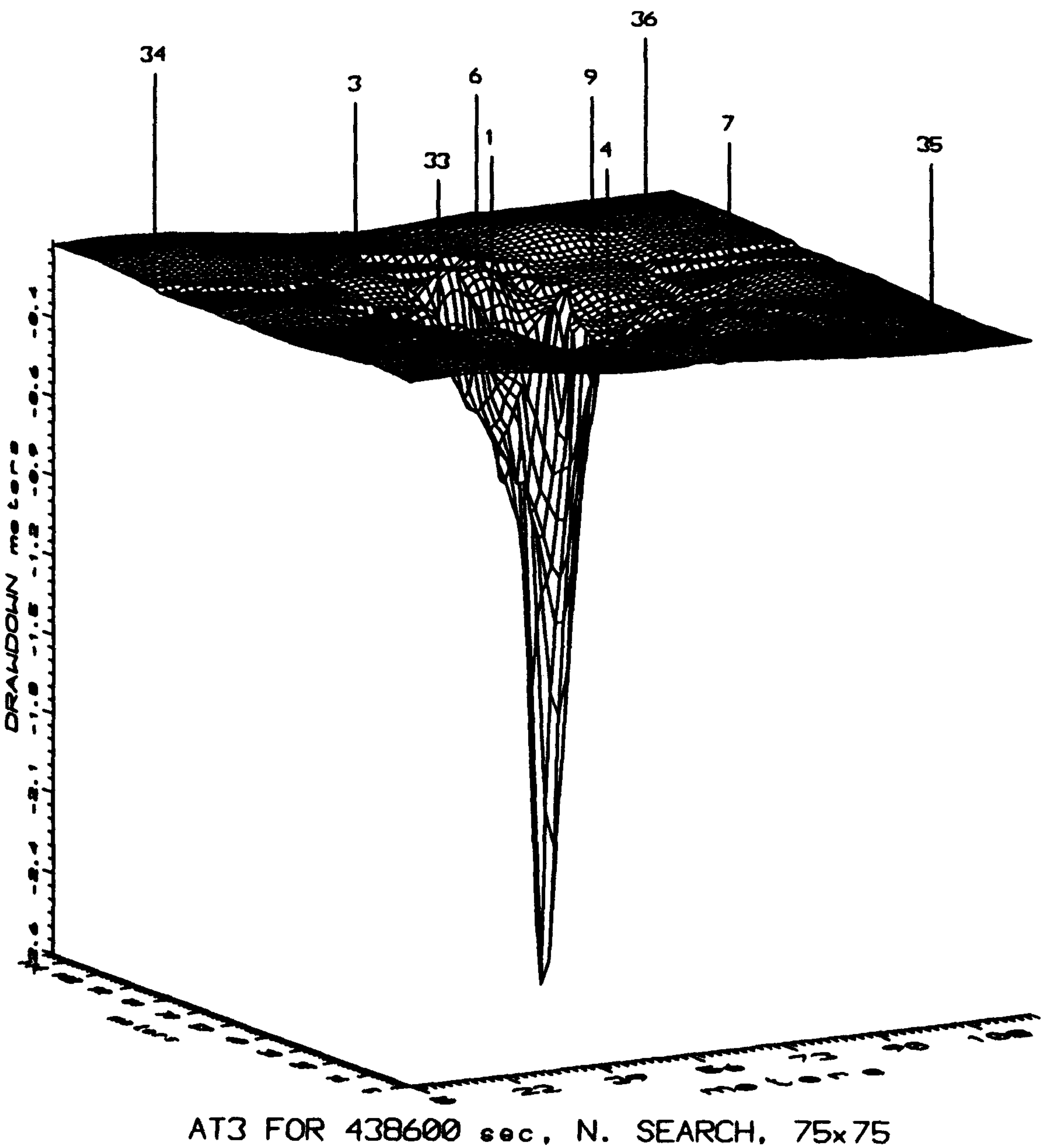


Figure 27. Three-Dimensional Map of the Aquifer Test 3 Final Drawdowns.

resulted from the method used to detrend the data. It is possible that less drawdown occurred at Wells 1 and 3, rather than at the other wells, because of natural temporal and spatial groundwater fluctuations. Third, the decreases may have resulted from equilibration processes acting within the aquifer. Over time, the hydraulic head gradients change which results in flow pattern changes to the pumped well. It is entirely possible that, at late times, the contribution from the eastern region to the total discharge increased as the total aquifer system reached equilibrium. This change would have lead to reduced gradients and declines of the drawdowns in the western region.

2. Transmissivities and Storage Coefficients From Program WELTEST

The WELTEST program was used to determine transmissivity and storage coefficient values at the locations of the twelve observation wells equipped with transducers. Input to WELTEST included the pumping schedule in Table 17, a saturated thickness of 7 meters, and an unconfined aquifer. WELTEST was applied to data sets for 10,000; 50,000; 100,000; and 250,000 seconds in order to investigate the sensitivity of the calculated hydraulic parameters with respect to time.

Table 18 lists the combination of transmissivity and storage coefficient values that provided the time-drawdown curve that best fit the observed time-drawdown curve as determined by the program WELTEST. Included in Table 18 are the factors by which the best value for either the transmissivity and the storage coefficient values can be multiplied or divided so that the calculated residual is increased to 0.10 and to 0.20. These adjustment factors are a measure of the sensitivity of the final answer to both transmissivity and the storage coefficient. Table 12 shows that the match between the observed and the predicted time-drawdown curves is more sensitive to the storage coefficient than to the transmissivity. No values are listed for a residual interval, when the "best" set of transmissivity and storage coefficient values lead to a residual that is greater than the designated residual. No results are provided for Wells 1 and 8 for times greater than 10,000 seconds because the residual calculated for the best set of transmissivity and storage coefficient values were greater than a residual of 20 percent.

TABLE 18. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 3 AT 10,000; 50,000; 100,000; AND 250,000 SECONDS

Well	Time (seconds)	Transmissivity Value	Transmissivity 10%	Transmissivity 20%	Storage Coefficient Value	Storage Coefficient 10%	Storage Coefficient 20%
1	10K	345.16	*/1.10	*/1.29	.00537	*/1.35	*/2.24
2	10K	194.10	*/1.15	*/1.32	.01047	*/1.38	*/1.95
4	10K	203.24	*/1.12	*/1.29	.00288	*/1.62	*/2.57
6	10K	104.24	*/1.12	*/1.32	.00537	*/1.45	*/2.09
8	10K	88.72	*/1.15	*/1.32	.00776	*/1.35	*/1.91
14	10K	53.46	*/1.12	*/1.26	.00013	*/2.24	*/5.13
17	10K	77.27	*/1.12	*/1.26	.00048	*/1.86	*/3.63
20	10K	55.98	*/1.12	*/1.26	.00029	*/2.14	*/4.47
25	10K	54.70	*/1.15	*/1.32	.01413	*/1.41	*/2.00
26	10K	19.41	NC	*/1.29	.00708	NC	*/1.51
30	10K	95.06	*/1.12	*/1.29	.00126	*/1.70	*/2.95
31	10K	165.20	*/1.00	*/1.32	.03715	*/1.00	*/1.48
1	50K	-	NC	NC	-	NC	NC
2	50K	116.95	*/1.10	*/1.32	.01995	*/1.29	*/1.91
4	50K	29.38	NC	*/1.17	.07244	NC	*/1.15
6	50K	30.06	NC	*/1.32	.03715	NC	*/1.38
8	50K	-	NC	NC	-	NC	NC
14	50K	43.45	*/1.12	*/1.26	.00051	*/2.09	*/4.37
17	50K	35.32	*/1.07	*/1.29	.00912	*/1.29	*/2.09
20	50K	31.48	*/1.12	*/1.26	.00457	*/1.55	*/2.63
25	50K	36.14	*/1.12	*/1.32	.02884	*/1.29	*/1.82
26	50K	25.59	*/1.07	*/1.26	.00398	*/1.32	*/2.09
30	50K	43.45	*/1.10	*/1.29	.01318	*/1.29	*/1.86
31	50K	52.24	NC	*/1.35	.10000	NC	*/1.32
1	100K	-	NC	NC	-	NC	NC
2	100K	99.54	*/1.10	*/1.32	.03020	*/1.29	*/2.04
4	100K	36.14	*/1.07	*/1.32	.06026	*/1.12	*/1.55
6	100K	26.79	*/1.10	*/1.32	.04266	*/1.17	*/1.55
8	100K	-	NC	NC	-	NC	NC
14	100K	30.06	*/1.12	*/1.26	.00407	*/1.82	*/3.39
17	100K	23.34	*/1.07	*/1.26	.02512	*/1.17	*/1.86
20	100K	26.79	*/1.12	*/1.26	.00871	*/1.62	*/2.75
25	100K	42.46	*/1.12	*/1.29	.01995	*/1.48	*/2.29
26	100K	28.06	*/1.10	*/1.26	.00282	*/1.51	*/2.57
30	100K	37.85	*/1.12	*/1.29	.01862	*/1.38	*/2.09
31	100K	48.75	*/1.10	*/1.35	.10000	*/1.15	*/1.48
1	250K	-	NC	NC	-	NC	NC
2	250K	90.79	*/1.10	*/1.29	.03715	*/1.38	*/2.34
4	250K	32.96	*/1.12	*/1.32	.06761	*/1.32	*/1.82
6	250K	28.06	*/1.12	*/1.32	.03890	*/1.38	*/1.95
8	250K	-	NC	NC	-	NC	NC
14	250K	28.71	*/1.12	*/1.26	.00513	*/1.95	*/3.98
17	250K	17.30	*/1.10	*/1.26	.05370	*/1.32	*/2.00
20	250K	25.00	*/1.12	*/1.26	.01148	*/1.74	*/3.16

TABLE 18. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 3 AT 10,000; 50,000; 100,000; AND 250,000 SECONDS (CONCLUDED)

Well	Time (seconds)	Transmissivity Value	10%	20%	Storage Coefficient Value	10%	20%
25	250K	21.28	*/1.05	*/1.29	.10000	*/1.15	*/1.95
26	250K	30.06	*/1.12	*/1.26	.00219	*/1.78	*/3.39
30	250K	38.73	*/1.12	*/1.29	.01738	*/1.58	*/2.57
31	250K	43.45	*/1.12	*/1.32	.09550	*/1.26	*/1.78

K = 1,000
NC = not calculated
*/ = multiplied or divided by

The trends shown in Table 18 are the same as those shown in Table 12 for Aquifer Test 1. In general, as the time period increases the variability decreases, the average transmissivity decreases, and the average storage coefficient increases. For time periods of 10,000; 50,000; 100,000; and 250,000 seconds the average transmissivities (excluding Wells 1 and 8) are 102, 44, 40, and 36 cm^2/s, respectively, and the average storage coefficients (excluding Wells 1 and 8) are 0.008, .029, .031, and .042, respectively. The trends in the transmissivities and storage coefficients are very similar to those observed for Aquifer Test 1. A possible explanation for these trends is discussed in subsection D of this section.

A comparison of the predicted and observed drawdown curves for all twelve wells for the four time periods is shown in Figures 28 to 31. For each of the figures, the predicted drawdown curve for each time period has been extrapolated to the end of the test to predict the final drawdowns. Several interesting features should be noted. First, as was true of Aquifer Tests 1 and 2, the drawdown response at Well 8 is very non-classical and cannot be adequately reproduced by WELTEST. Second, the plotted data approximates a straight-line shortly after the pumping started to about 200,000 seconds. Third, after 200,000 seconds, some type of boundary condition, a delayed drainage phenomena, and/or change in the pumping rate prevents additional drawdown at all of the wells.

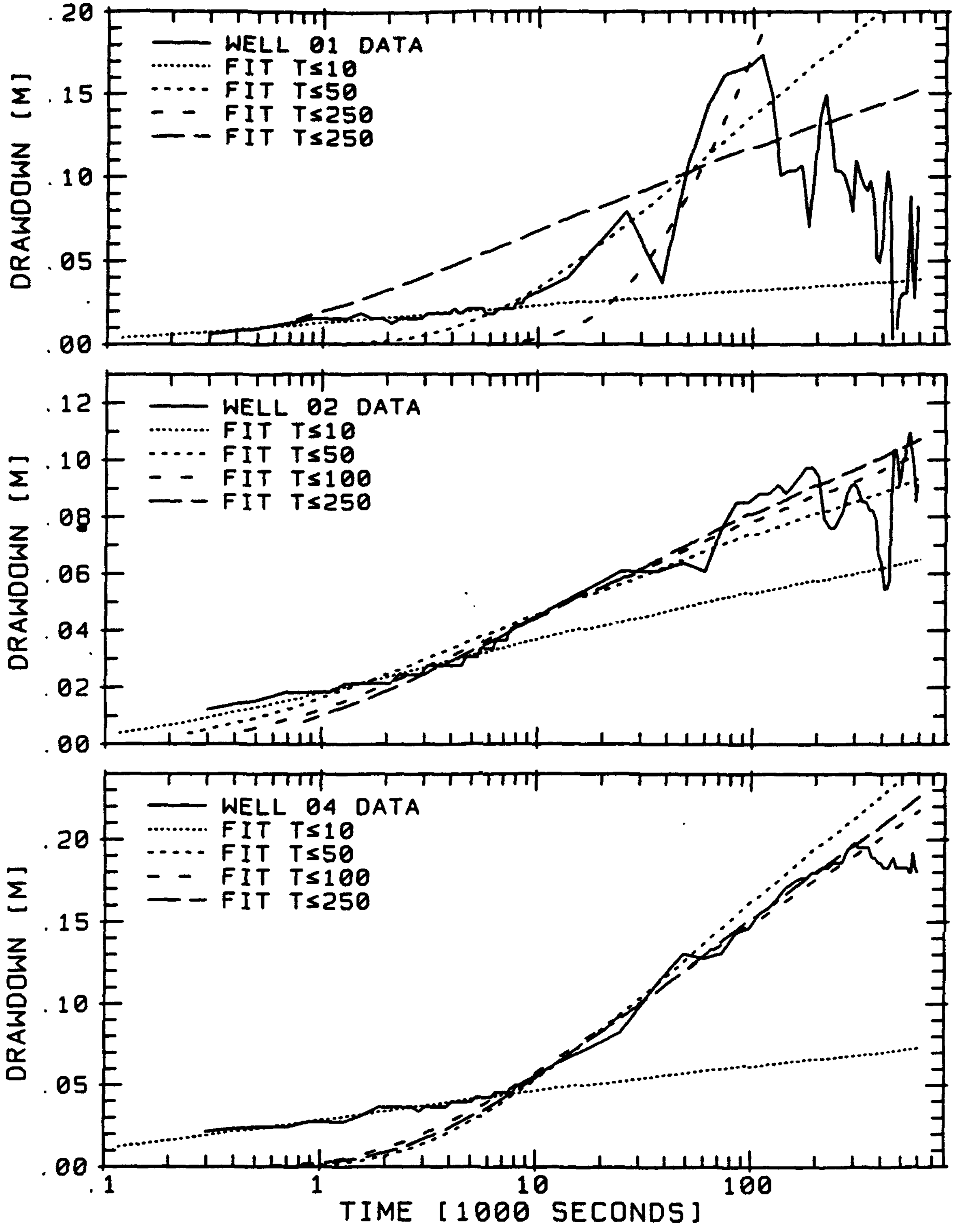


Figure 28. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 1, 2, and 4.

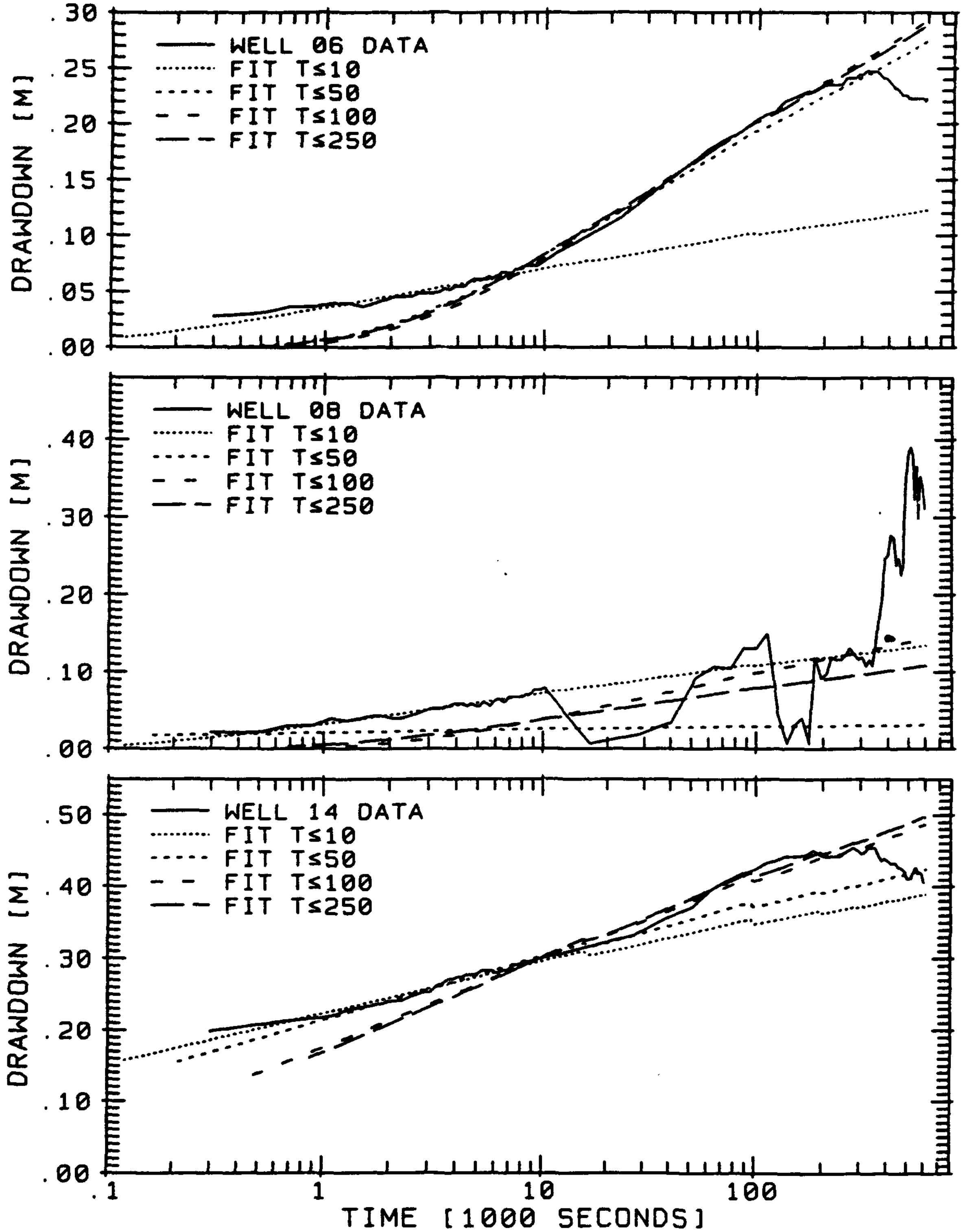


Figure 29. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 6, 8, and 14.

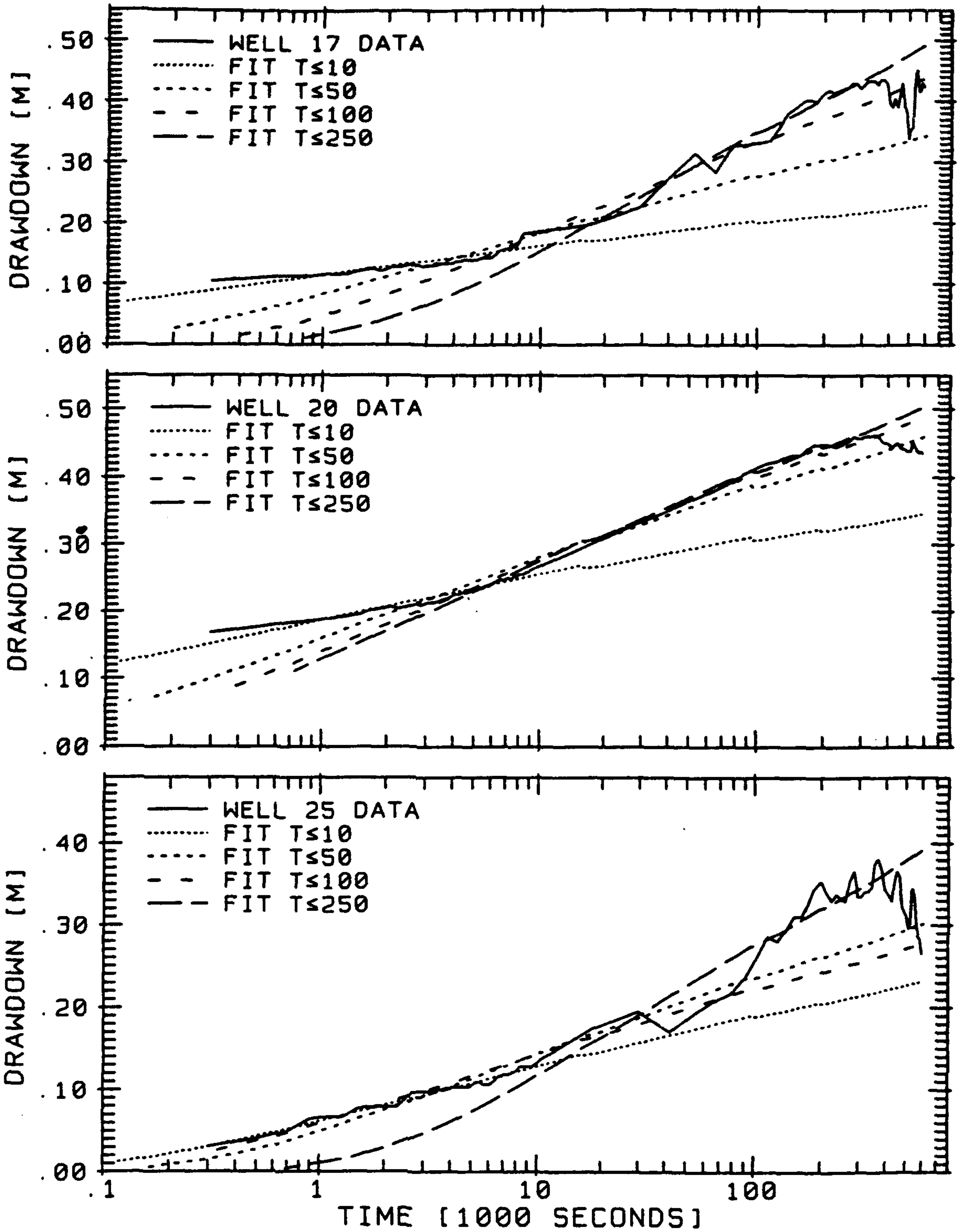


Figure 30. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 17, 20, and 25.

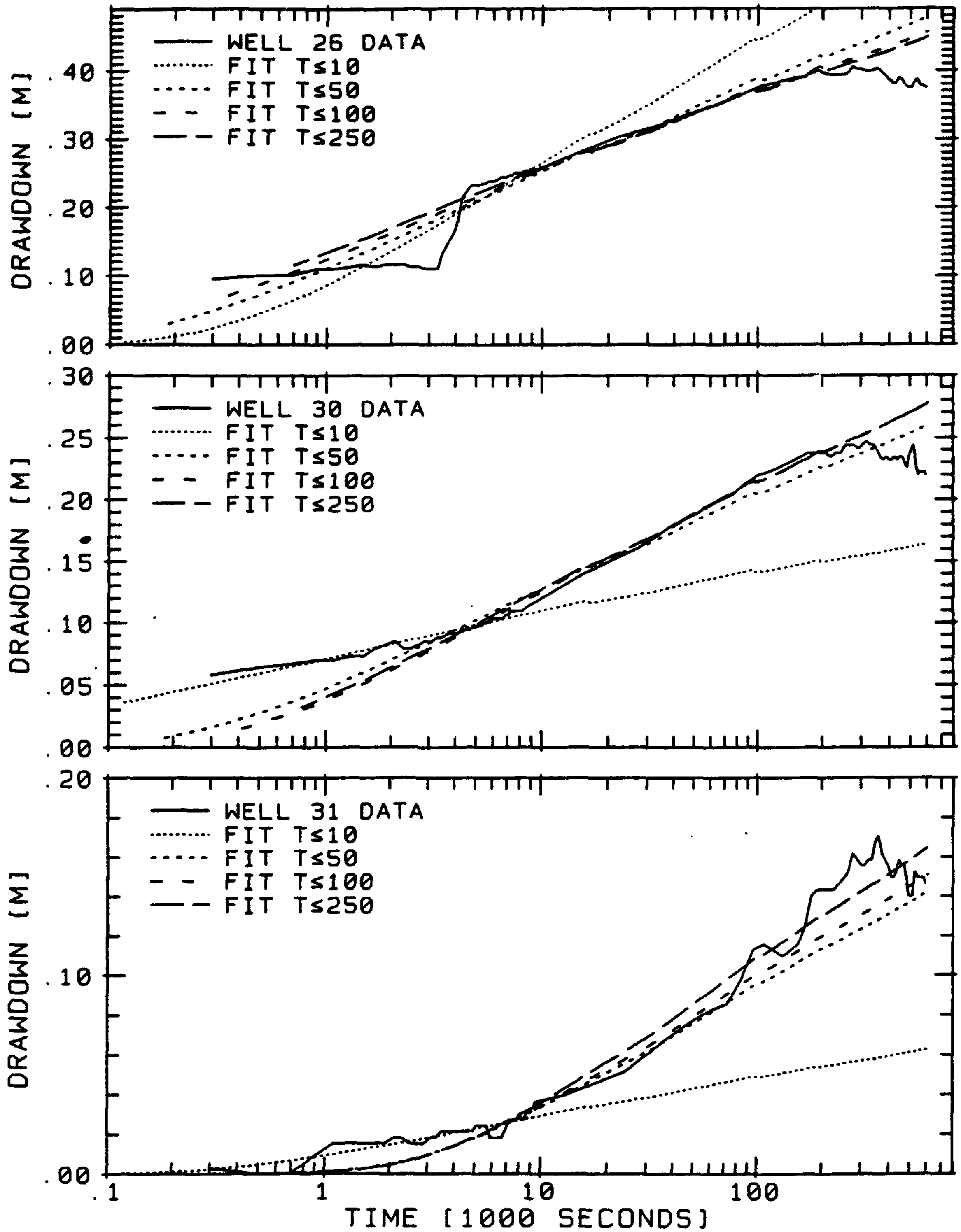


Figure 31. WELTEST Fits to Aquifer Test 1 Drawdowns for Wells 26, 30, and 31.

3. Transmissivities by the Cooper-Jacob Straight-Line Method

As discussed in Section IV B, the Cooper-Jacob analysis at large dimensionless time is preferred over the Theis-based curve fitting technique for determining values of transmissivities for a distributed-parameter model. As such, the Cooper-Jacob analysis is used here to determine the averaged transmissivity value of the aquifer. Based on Figure 26, the influence of the pumping well was not great enough to perform a reliable analysis of all 37 wells, so only the interior 27 wells were analyzed.

The slopes of the time-drawdown curves were calculated as described in the discussion of Aquifer Test 1 data. The slopes were evaluated using data taken between 70,000 seconds and 200,000 seconds. At wells where transmissivities were calculated using both transducer and manual measurements, the transducer-based transmissivity estimate was considered more accurate. Table 19 lists the transmissivities calculated by the Cooper-Jacob straight-line method for Aquifer Test 3.

The arithmetic and geometric means for the 27 transmissivity values in Table 19 are 33 and 31 cm^2/s, respectively. The standard deviation for the transmissivities is 12.9 cm^2/s. Variations in the transmissivity indicate a region of high values in the western region (Wells 1, 2, 3, and 18). Values of low transmissivity appear to be scattered throughout the well network.

TABLE 19. TRANSMISSIVITIES CALCULATED BY THE COOPER-JACOB STRAIGHT-LINE METHOD FOR AQUIFER TEST 3

Well	T (cm^2/s)	Well	T (cm^2/s)	Well	T (cm^2/s)	Well	T (cm^2/s)
1	62	10	24	19	26	28	-
2	60	11	26	20	24	29	-
3	56	12	27	21	28	30	36
4	32	13	26	22	-	31	32
5	20	14	29	23	-	32	34
6	31	15	28	24	25	33	-
7	36	16	34	25	25	34	-
8	30	17	17	26	33	35	-
9	38	18	46	27	-	36	-

G. SMALL-SCALE AQUIFER TEST

The small-scale aquifer tests consisted of pumping a well at a constant rate between 2 and 3 hours and measuring the drawdown in nearby wells with pressure transducers. The tests were performed to determine whether the location and/or the rate of the pumping well, relative to the observation well, affected the calculated values of transmissivity and storage coefficient. A total of seven small-scale aquifer tests were conducted. Table 20 summarizes the specific details for each test. The tests were conducted over a 5-month period. The water table changed less than 0.5 meters between the April and July tests and less than 0.1 meters between the June and July tests.

TABLE 20. THE LOCATION OF THE MONITORING AND PUMPING WELLS FOR THE SMALL-SCALE AQUIFER TESTS

Pumped Well	Date	Flow Rate (L/min)	Duration (seconds)	Observation Wells
12[2]	7/27/89	60.4	8,631	8,10,12,13,15,17,21,24,25,31,32
13[1]	6/29/89	77.2	3,394	5,13,14,16,18,19
16[1]	7/27/89	81.0	8,646	5,10,11,13,14,16,17,18,19,20,25,26
19[1]	4/20/89	34.0	2,736	13,14,16,19
24[2]	4/20/89	34.0	3,400	10,12,25
25[2]	6/28/89	77.2	3,852	10,12,21,24,25,32
31	7/28/89	55.1	9,075	8,9,10,11,12,15,16,17,20,25,26,31

[1]Wells located in the northwest well cluster
[2]Wells located in the eastern well cluster

As shown in Table 20 the aquifer tests centered on two clusters. One well cluster (Wells 5, 13, 14, 16, and 19) is located about 5 meters northwest of the well network's center. The other well cluster (Wells 8, 10, 12, 24, and 25) is located about 11 meters west of the well network's center. At each of these well clusters, three small-scale aquifer tests were performed.

During the seven small-scale aquifer tests, a total of 54 wells were monitored for drawdown. Of these 54 well records, only 33 well records were suitable for analysis; the remaining well records were not analyzed because of the relative small drawdown values or because the well was the

pumping well. Because of the relatively short duration of the tests, no detrending of the data was performed before WELTEST was applied to the data sets. Several of the data sets had fluctuations or sharp changes in the water table levels toward the end of the tests. Before these data sets were analyzed the latter portion of the data was removed. Table 21 provides the WELTEST results for the 33 suitable well records.

Results in Table 21 show generally higher values of transmissivity and lower values of storage coefficient for the 13-16-19 well cluster than the 12-24-25 well cluster. This trend in the hydraulic properties among these wells is qualitatively consistent with the results of the large-scale aquifer tests. However, the magnitude of the values calculated from the large- and small-scale aquifer tests differ. The most prominent difference is in the storage coefficient values: small-scale aquifer tests have storage coefficients values that are one to three orders of magnitude lower than the values for the large-scale test. These results support the aforementioned speculation of scale-dependent storage coefficient values (see subsection E of this section).

As shown in Table 21, two of the three pumping rates for each well cluster were about twice that of the lowest pumping rate. For both well clusters, the lowest pumping rate provided significantly smaller values of transmissivity. For the 13-16-19 well cluster, the lowest pumping rate provided significantly higher values of storage coefficients than did the two higher pumping rates. At the two higher pumping rates, the results in Table 21 show that at some of the observation wells, the calculated values of transmissivity and storage coefficient changed with a change in the pumping well location.

In general, the results in Table 21 indicate that the calculated values of transmissivity and storage coefficient at a location of an observation well are affected by the orientation and distance between the observation and pumping well and may be affected by the pumping rate. The sensitivity of the calculated transmissivity and storage coefficient values to the changes in the pump test are different. The storage coefficient values are extremely sensitive, whereas the transmissivity values are moderately sensitive to these changes.

TABLE 21. WELTEST CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR THE SMALL-SCALE AQUIFER TESTS

Well Pair	Rate (l/min)	T (cm^2/s)	10%	20%	S	10%	20%
Well Cluster 1							
13- 5	77.2	46.56	*/1.10	*/1.26	.00036	*/1.82	*/3.72
13-14	77.2	52.24	*/1.07	*/1.23	.00004	*/1.95	*/5.25
13-16	77.2	47.64	*/1.10	*/1.23	.000005	*/2.57	*/6.17
13-18	77.2	169.05	*/1.12	*/1.26	.00046	*/1.82	*/3.39
13-19	77.2	45.50	*/1.07	*/1.23	.00003	*/2.09	*/6.46
16- 5	81.0	65.77	*/1.10	*/1.23	.00002	*/2.57	*/7.76
16-13	81.0	65.77	*/1.10	*/1.23	.000001	*/1.00	*/1.32
16-14	81.0	65.77	*/1.12	*/1.23	.000011	*/3.16	*/10.0
16-19	81.0	44.46	*/1.10	*/1.23	.000004	*/2.95	*/6.46
16-13	81.0	47.64	*/1.07	*/1.23	.00001	*/2.57	*/7.41
16-14	81.0	65.77	*/1.12	*/1.23	.00001	*/3.16	*/10.0
16-19	81.0	41.50	*/1.10	*/1.23	.00001	*/2.69	*/8.71
16-20	81.0	62.81	*/1.12	*/1.26	.00040	*/1.82	*/3.55
16-26	81.0	72.11	*/1.12	*/1.26	.00010	*/2.00	*/4.07
19-13	34.0	22.80	*/1.12	*/1.29	.00135	*/1.70	*/2.88
19-14	34.0	26.18	*/1.12	*/1.26	.00123	*/1.82	*/3.31
19-16	34.0	21.78	*/1.12	*/1.26	.00089	*/1.70	*/2.95
Well Cluster 2							
12- 8	60.4	36.14	*/1.12	*/1.29	.00100	*/1.70	*/2.88
12-10	60.4	26.79	*/1.10	*/1.26	.00068	*/1.86	*/3.72
12-11	60.4	45.50	*/1.12	*/1.26	.00025	*/1.82	*/3.31
12-15	60.4	37.85	*/1.10	*/1.23	.00002	*/2.04	*/5.25
12-21	60.4	25.59	*/1.07	*/1.26	.00129	*/1.35	*/2.24
12-24	60.4	30.06	*/1.12	*/1.26	.00155	*/1.78	*/3.24
12-25	60.4	46.56	*/1.10	*/1.23	.00005	*/1.95	*/5.01
24-10	34.0	21.28	*/1.12	*/1.29	.00263	*/1.51	*/2.29
24-12	34.0	20.32	*/1.10	*/1.26	.00331	*/1.48	*/2.45
24-25	34.0	24.44	*/1.12	*/1.29	.00162	*/1.62	*/2.63
25-10	77.2	36.14	*/1.12	*/1.26	.00214	*/1.70	*/2.95
25-12	77.2	61.38	*/1.10	*/1.23	.00005	*/1.95	*/5.25
25-21	77.2	44.46	*/1.12	*/1.26	.00042	*/1.78	*/3.24
25-24	77.2	36.14	*/1.12	*/1.29	.00537	*/1.51	*/2.34
25-32	77.2	52.24	*/1.12	*/1.32	.00214	*/1.41	*/2.00
Pump Test at Well 31							
31-11	55.1	51.05	*/1.10	*/1.26	.00038	*/1.78	*/3.39
31-15	55.1	28.71	*/1.07	*/1.23	.00006	*/1.74	*/4.27
31-20	55.1	52.24	*/1.10	*/1.26	.00042	*/1.58	*/2.82

Note: The first and second values listed in the well pair are the pumping well and observation well, respectively.

*/ = multiplied or divided by

SECTION VI

ANALYSIS OF THE THEIS-BASED TRANSMISSIVITIES AND STORAGE COEFFICIENTS

A. DRAWDOWN DURING AN AQUIFER TEST

1. Homogeneous Aquifer

At the beginning of an aquifer test, the rate of change in the water table level will be greater than at other times because only a small portion of the aquifer contributes to the discharge. During this initial period, the pressure gradients change rapidly to increase the groundwater flow from the more distant aquifer material that surrounds the pumping well. As time increases, most of the discharge originates from aquifer material further away from the pumping well. During the intermediate and late period, the change in pressure gradients is gradual since they need only to maintain the groundwater flow to the well from the aquifer material far away from the well.

For a homogeneous aquifer, the small volume of aquifer that initially contributes to the discharge is from a concentric cylinder of aquifer material adjacent to the well. As time passes, the size of this concentric cylinder expands and the pressure distribution across the cone-of-depression can be represented by a series of concentric circles of equal-potential. Because of the homogeneity of the aquifer, no vertical gradients exist.

2. Heterogeneous Aquifer

In a heterogeneous aquifer that contains lenses, all of the aquifer volume that initially contributes to the discharge is not necessarily close to the well. In a heterogeneous aquifer, the zones of highest diffusivities will have the largest radius of influence at any time. The orientation and location of the zones of high diffusivity and the amount of contrast in the diffusivities of the different aquifer materials will determine from where in the aquifer the discharge

originates. In general, the greater the difference among the layers, the more quickly the pressure response will be transmitted laterally through the zones of high diffusivity.

Because the initial pressure change in the pumping well fingers nonuniformly into the aquifer, vertical pressure gradients are established quickly. As a consequence, the pressure at different locations along a vertical line through the aquifer will not be equal. In fact, large pressure gradients may exist between the higher diffusivity zones, which respond relatively quick, and the lower diffusivity zones, which respond relatively slow.

3. Storage Coefficient and the Specific Yield

a. Definitions

The specific storage, S_o, for either a confined or unconfined aquifer is defined as the volume of water that a unit volume of aquifer releases from artesian storage under a unit decline in hydraulic head. The water that is released from artesian storage under conditions of decreasing hydraulic head is produced by two mechanisms: (1) the compaction of the aquifer caused by increasing effective stress, and (2) the expansion of water caused by decreasing hydraulic pressure. The specific yield, S_y, for an unconfined aquifer represents the amount of water that is released per unit surface area of aquifer per unit decline in the water head. In more general but less precise terminology, the specific yield is the water released from drainage as the water table is lowered in an unconfined aquifer.

The storage coefficient for confined aquifers is equal to the specific storage whereas the storage coefficient for the unconfined aquifer is equal to the sum of the specific storage and the specific yield. Often, the contribution of the specific storage to the storage coefficient of an unconfined aquifer is considered small compared to the contribution of the specific yield. In these cases, the terms storage coefficient and specific yield are used interchangeably. Typical values provided for the range of specific storages and specific yields given by

Freeze and Cherry (1975) are 0.005 to 0.00005 and 0.01 to 0.30, respectively.

b. Different Methods for Calculating Specific Yields

Based on the WELTEST analysis of Aquifer Test 2, the estimated specific yield for the unconfined aquifer at the test site is 0.03. Besides the analysis of aquifer tests by the application of type curves, specific yields can be estimated by laboratory drainage experiments on samples of the aquifer material and by measured fluctuations of the water table. Fortunately, enough data can be collected at or near the test site to compare the specific yield calculated from the type curves to the two different methods for calculating specific yield.

With regard to laboratory drainage experiments, the specific yield is often computed as the difference between the saturated and the residual water content. Based on the analysis of 84 minimally disturbed 15-cm long saturated soil cores taken at the MADE site, the estimated saturated water content of the Columbus AFB terrace aquifer is 0.32 (Boggs, et al., 1990). In the laboratory, the saturated cores were drained at a pressure of about 4 bars for 20 minutes. At the end of the drainage period, the average moisture content in the cores was 0.17. Because of the relatively high pressures and short time period used to drain the sample, the value of 0.17 should be considered as a rough but adequate estimate of the specific yield.

Based on pumping well data, geohydrologists have applied Equation (21) to calculate specific yield by the volume-balance method (Wenzel, 1942; Remson and Lang, 1955; and Nwankwor, et al., 1984). In Equation (21), V_d is the cumulative volume of water discharged from a well during an aquifer test, and V_i is the volume when the cone-of-depression is integrated.

$$S_y = V_i/V_d \qquad (21)$$

Using Equation (21), Figure 32 was created to show that neither the 0.03 estimate, provided by the aquifer type curves, nor the 0.17 estimate, provided by the drainage experiment, provides a good match between the values of V_d and V_i. In fact, the general shape of the plot between the values of V_d and V_i are very different and indicate that the only way in which agreement between V_i and V_d will occur is if the specific yield is time dependent. By applying Equation (21) to their respective data sets, several researchers have observed the specific yield estimates to increase over time (Wenzel, 1942; Remson and Lang, 1955; and Nwankwor, et al., 1984). As shown in Table 22, the application of Equation (21) to the results in Aquifer Tests 1 and 3 produce the type of temporal trends in specific yield reported by earlier investigators.

TABLE 22. SPECIFIC YIELD ESTIMATES BASED ON A VOLUMETRIC WATER BALANCE FOR AQUIFER TESTS 1 AND 2

Aquifer Test 1		Aquifer Test 2	
Time (hours)	Estimated S_y*	Time (hours)	Estimated S_y*
4.3	0.03	5.4	0.04
27.7	0.11	26.4	0.12
47.0	0.19	52.9	0.22
98.6	0.37	99.9	0.38
120.0	0.47	121.8	0.49

*S_y is calculated based on Equation (21) and results of the integration of the cone-of-depression by the program SURFER (Golden, 1989).

c. Usefulness of the Different Methods for Calculating Specific Yields

The results in Table 22 are similar to the results obtained by Nwankwor, et al. (1984), for a 65-hour pump test in an unconfined sand aquifer composed of glacial till. Nwankwor, et al. (1984), applied the volume-balance method and produced specific yield values of 0.02, 0.05, 0.12, 0.20, 0.23, and 0.25 at times of 0.25, 0.66, 10, 26, 45, and 65 hours, respectively. Nwankwor, et al. (1984), compares the trend in the specific yield values to the 0.30 value calculated from a laboratory drainage experiment and concludes, based on several hypotheses, that "type-curve procedures therefore provide unrealistically low values

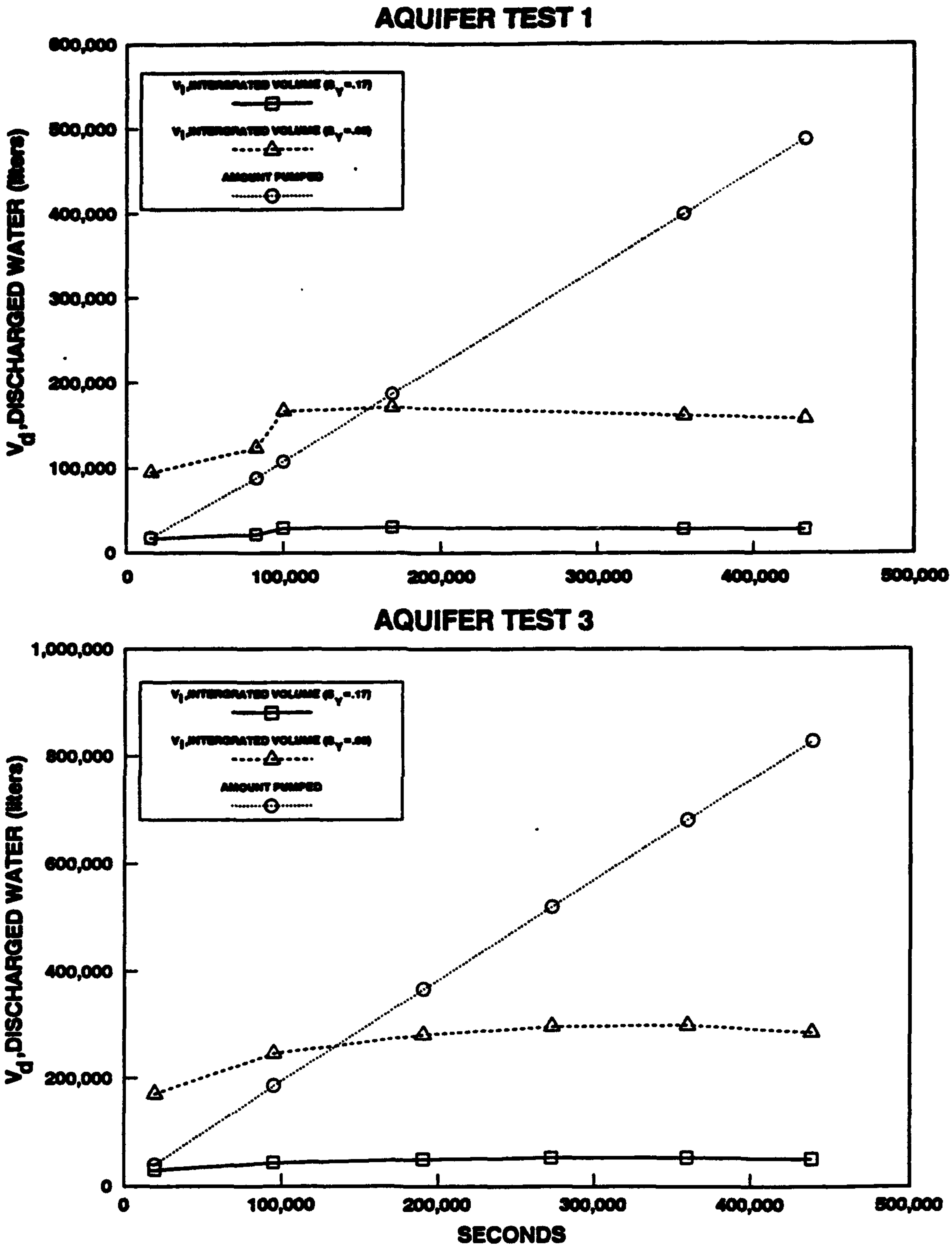


Figure 32. Volume of Groundwater Calculated From the Cone-of-Depression and From the Pumping Schedule for Aquifer Tests 1 and 3.

(i.e., 0.07 and 0.08) of specific yield for applications to problems concerning the long-term yield characteristics of the aquifer."

In response to the trends and the conclusions published by Nwankwor, et al. (1984), Neuman (1988), reevaluates the data and shows several problems with the analyses of Nwankwor, et al. (1984), and demonstrates that the type-curve specific yield values of 0.07 and 0.08 are entirely consistent with a volumetric analysis, when the analysis is done correctly. Among the important conclusions given by Neuman (1988), which are valuable to any site characterization study, are the two following statements.

"1. Water-balance methods in which specific yield is computed from pumping test data by assuming that all the discharge derives from drainage within the observed cone-of-depression may lead to error of several hundred percent. Theory shows and the Borden test confirms that significant amounts of water are released from storage by gravity drainage outside the observed cone-of-depression even though the drawdowns there may be imperceptible. Neglecting this source of water results in exaggerated values of specific yield. It further leads to the erroneous impression that the specific yield grows with time as the pumping test progresses.

2. Specific yields determined from drainage experiments on samples of aquifer material in the laboratory are often much larger than values obtained from pumping tests in the field. This is especially true when the specific yield is taken to be the difference between the water content at saturation and the residual content at high suctions. According to Nwankwor, et al. (1984), the time required for equilibrium to be reached when the sandy Borden aquifer material was subjected to stepwise increments of suction ranged from tens of minutes at high values of water content to 1 to 2 days at low values of water content. In the pumping test that lasted less than 3 days, the most rapid fall of the water table occurred during the first 10 hours. This shows that the water-table response to pumpage is a much faster phenomenon than drainage in the unsaturated zone above it. Since the two phenomena are characterized by different time scales, the variation of groundwater levels in response to pumpage is relatively insensitive to residual drainage in the unsaturated zone. A similar conclusion can be reached on the basis of a theoretical study conducted more than a decade ago by Kroszynski and Dagan (1975). It thus becomes clear that whereas specific yields obtained in the laboratory may be useful for the evaluation of groundwater reserves that may be potentially recoverable over long time periods, they are generally not relevant to the problem of relating groundwater level fluctuations to

pumpage. This latter problem, which arises in the majority of groundwater studies, requires specific yield values of the kind obtained from the analysis of time-drawdown data."

d. Summary of Results

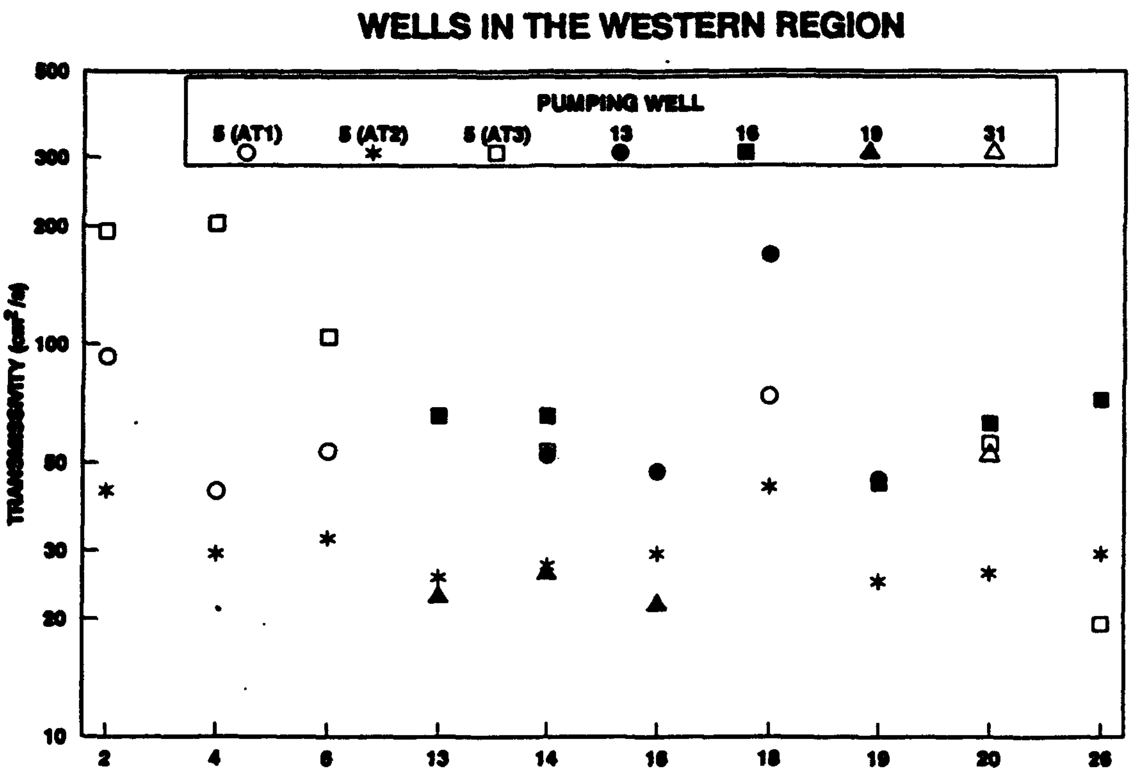
The results of the analysis of the aquifer test data for this project and for the Borden aquifer demonstrate that there is opportunity for confusion in understanding the physical meaning of a storage coefficient calculated for an unconfined aquifer. Although it includes components due to specific storage and a specific yield, the storage coefficient for an unconfined aquifer can be at least 500 percent less than the specific yield calculated for the aquifer based on laboratory drainage experiments. This difference occurs because the drainage from the unsaturated zone occurs at a much slower rate than the groundwater level fluctuations due to pumpage. Moreover, an in-depth review and application of the work of Neuman (1987), would show that the best method for calculating storage coefficients for unconfined aquifers is by using type-curve matching instead of volumetric water balance methods.

B. THE AQUIFER TEST RESULTS

1. General Observations

As discussed in Section III and Section IV, the hydraulic properties calculated from well drawdown data are affected not only by the aquifer material near the well, but also by the aquifer material within the cone-of-depression. In heterogeneous aquifers, the amount of influence that "near-field" and "far-field" aquifer materials have on the calculated hydraulic properties depends on the design of the aquifer test. Important aquifer test design parameters are: (1) the pumping rate, (2) the duration of the test, (3) the location of the pumping well, (4) the location of the observation well, (5) the procedures for collecting and analyzing the well data, and (6) whether the pumping well is injecting or withdrawing water.

Because the aquifer test design can affect the calculated hydraulic properties, Figures 33 and 34 were constructed to compare the



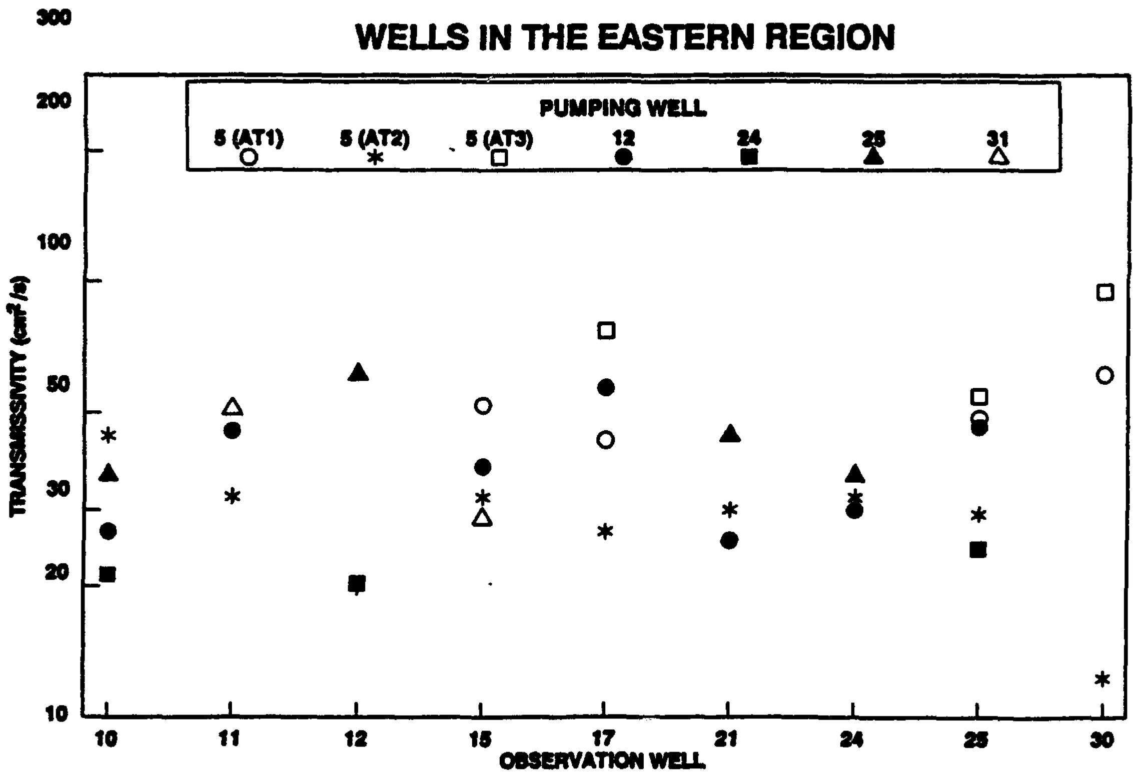


Figure 33. Comparison of Transmissivities Calculated From Different Aquifer Tests at the Same Well Location.

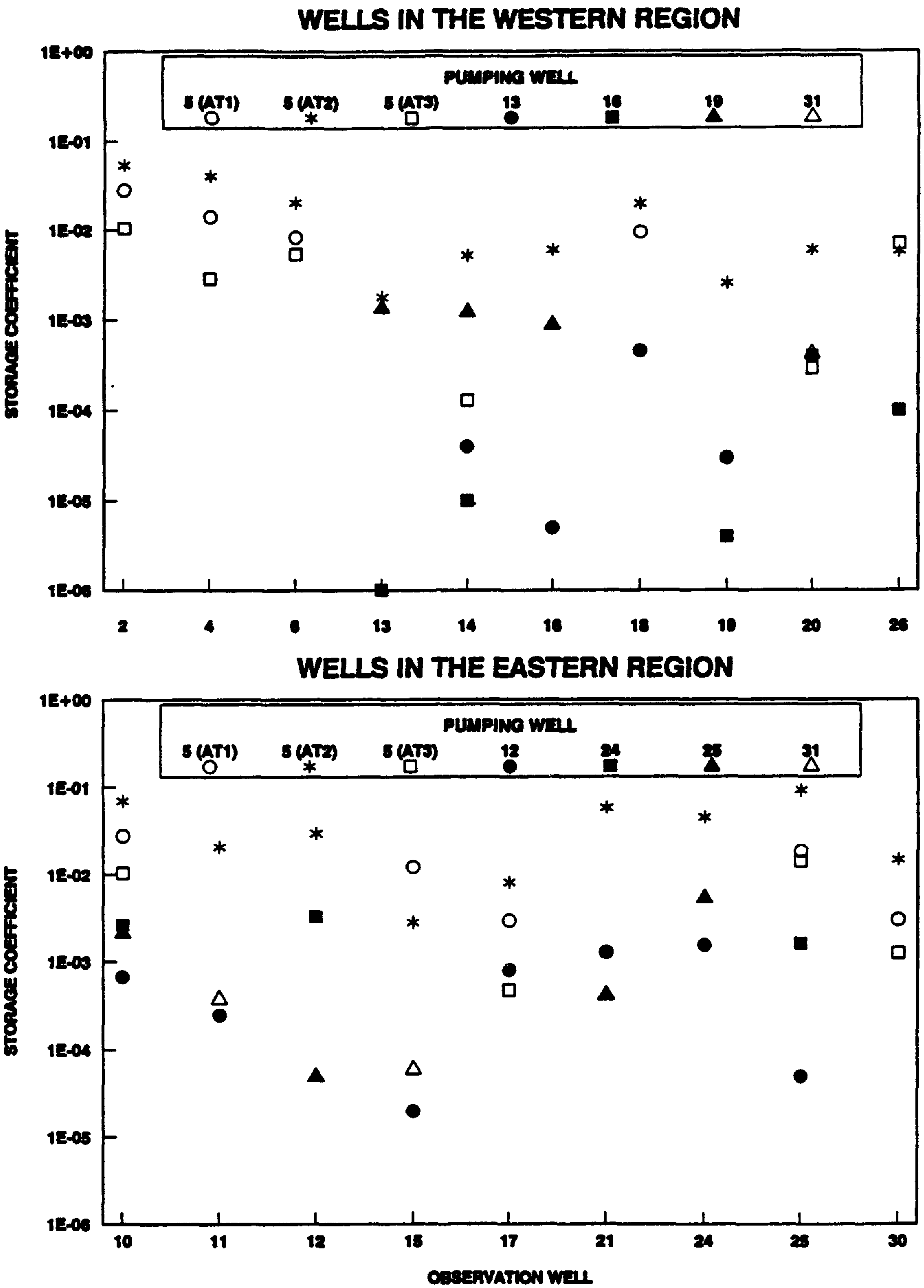


Figure 34. Comparison of Storage Coefficients From Different Aquifer Tests at the Same Well Location.

values of transmissivities and storage coefficients calculated at the same well location during the different aquifer tests. Section V discusses the design and the method of data analysis for the three large-scale and seven small-scale aquifer tests (Figures 33 and 34). In order to minimize the effect of the different durations between the small-scale and the large-scale tests, only the hydraulic values calculated at 10,000 seconds were used from the large-scale aquifer tests (The small-scale tests had durations between 3,000 and 9,000 seconds).

Figures 33 and 34 show considerably more variability among the storage coefficients than among the transmissivities. Whereas the storage coefficients vary over five orders of magnitude, the transmissivities vary, at most, one order of magnitude. These results indicate that the design of the aquifer test had a large impact on the calculated values for transmissivities and storage coefficients at the selected well locations.

Given a saturated aquifer thickness of about 7 meters, the values of the transmissivities result in a range of average hydraulic conductivities between 0.14 and 0.0014 cm/s. These hydraulic conductivity values are within the range of 0.001 to 1 cm/s that Freeze and Cherry (1976), indicated would be appropriate for a sand and gravel aquifer. The low values for the storage coefficients, however, are not consistent with the assumed unconfined property of the aquifer. Typically, unconfined aquifers have storage coefficients in the range between 0.3 and 0.01 and confined aquifers have storage coefficients between 0.005 to 0.00005 (Freeze and Cherry, 1976). The storage coefficient values at the test site span a range that includes values typical of unconfined, semi-confined, and confined aquifers.

2. Effect of the Distance Between Pumping and Observation Wells

a. The Observed Trend

In Section V, the aquifer data indicated a trend between the distance between the pumping and the observation wells and the value of the storage coefficient. Evidence for this trend includes: (1) all of

the storage coefficient values less than 0.01 for the large-scale aquifer tests occurred at the wells closest to the pumping well; and (2) the small-scale aquifer tests had storage coefficient values orders of magnitude smaller than for the large-scale aquifer tests.

In order to investigate this trend, all of the transmissivities and storage coefficients in Section V were plotted in Figure 35 as a function of distance. Figure 35 shows no trend between transmissivity and distance but does show a trend between the storage coefficient and distance. Table 23 summarizes the trend in the storage coefficient values shown in Figure 35. In general, at distances less than 10 meters, the storage coefficient values are within the range for confined aquifers. Storage coefficients for confined aquifers are determined by the water released from storage due to the expansion of water and the compression of the aquifer material that result from pressure changes. Unconfined aquifers typically have higher storage coefficient values than confined aquifers because water released from storage is from the same mechanisms active in confined aquifers and from the dewatering of the water table.

TABLE 23. THE OBSERVED TREND BETWEEN STORAGE COEFFICIENT VALUES AND THE DISTANCE BETWEEN THE OBSERVATION AND THE PUMPING WELLS

Distance Between Observation and Pumping Well (meters)	Range for the Storage Coefficient
0 to 10	10^{-6} to 10^{-2}
10 to 20	10^{-4} to 10^{-2}
>20	10^{-2} to 10^{-1}

b. Processes That Affect the Spatial Differences

A fictitious cross section of a heterogeneous unconfined aquifer is illustrated in Figure 36. If Well B in Figure 36 is pumped, the pressure response will be quickly transmitted to Well A because of the thin continuous lens of high hydraulic conductivity material that intersects both Wells A and B. At early times, a sharp difference in the pressures will exist in the less transmissive K_3 matrix and the highly conductive K_1 lenses. The water levels in Well A will reflect the

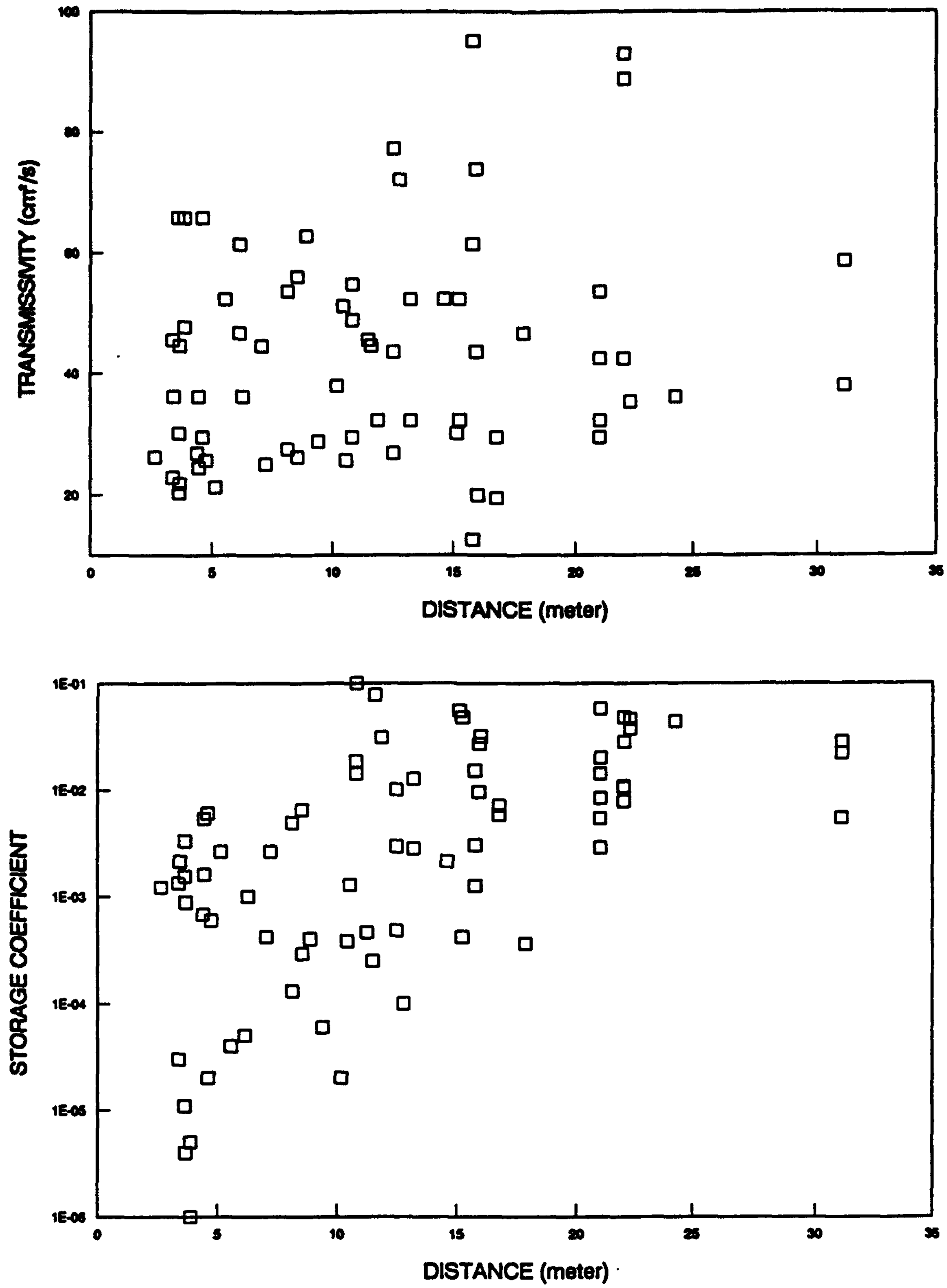


Figure 35. Transmissivities and Storage Coefficients as a Function of Distance Between the Observation and the Pumping Well.

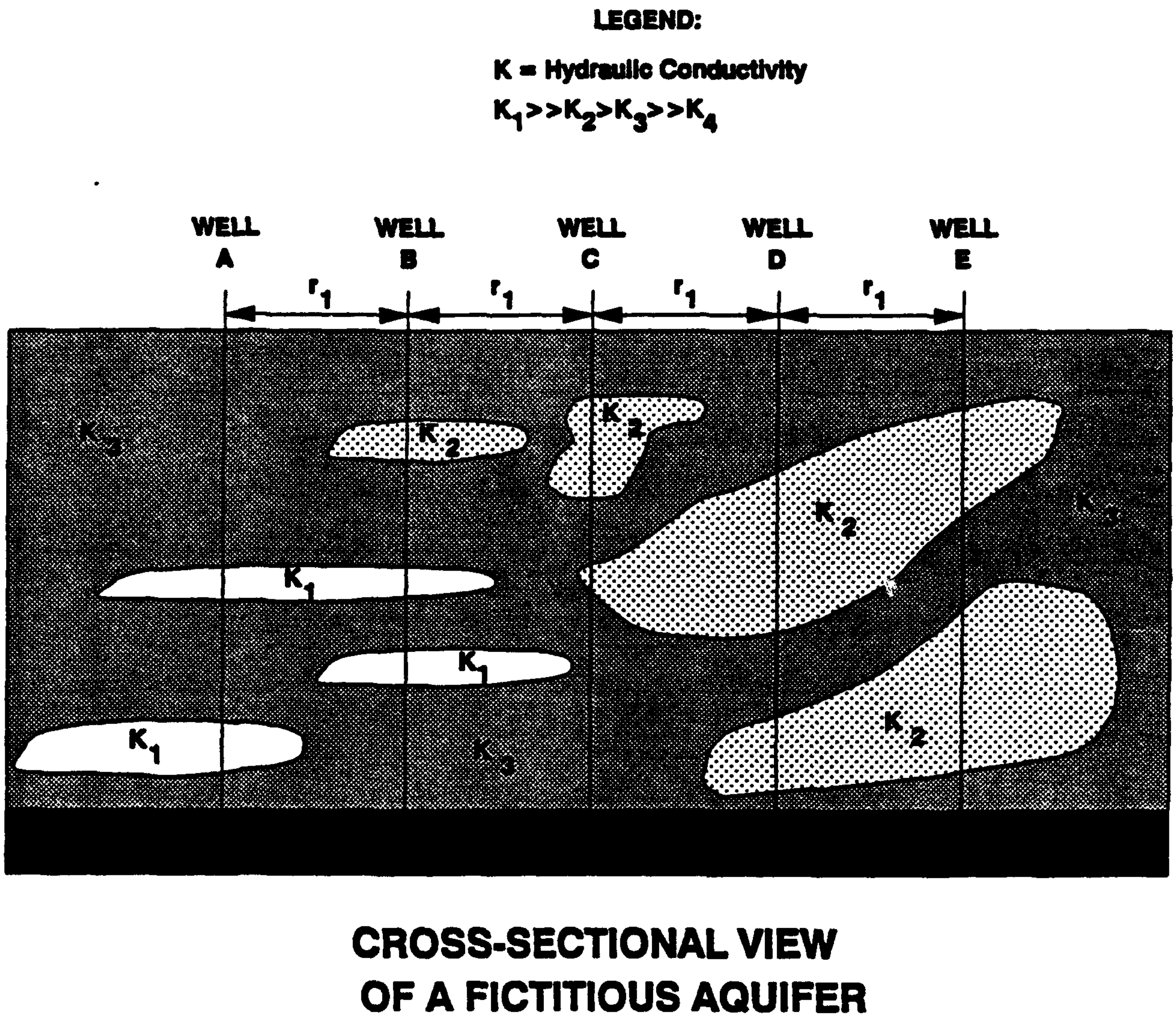


Figure 36. A Cross-Sectional View of a Fictitious Heterogeneous Aquifer.

pressure in the K_1 lens and the analysis of the water table at Well A will indicate that the aquifer is confined. However, as shown in Figure 36, the reason for this conclusion is not because the aquifer is confined, but rather because a layer of high hydraulic conductivity material, which is confined, intersects both the pumping and the observation wells.

When Well B is pumped, the pressure drops and travels toward C in lenses K_2 and K_1. Because neither lens intersects Well C, the relatively large pressure drop realized in lenses K_2 and K_1 is dissipated within the K_3 matrix before reaching Well C. Because the pressure response had to travel through both lenses of relatively high hydraulic conductivity and through the matrix of moderate hydraulic conductivity, the rate of drawdown in Well C will be less than in Well A. The analysis of the water table in Well C would provide a storage coefficient that is greater than Well A.

When Wells B and D are pumped, the distribution of flow and the vertical hydraulic gradients are very different near each of the wells. Near Well B, the pressure changes are initially transmitted by a small volume of the aquifer composed of zones of higher conductivity. As a consequence of the different pressure responses in the aquifer matrix and in the lenses, large vertical hydraulic gradients are created between the lenses and the matrix. Over time, the crossflow between aquifer matrix and the lenses leads to equilibrium of the pressures and, eventually, the phreatic surface comes into equilibrium with the pressures in the lenses. Near Well D, the pressure changes are initially transmitted by a large volume of the aquifer composed of a material slightly more conductive than the aquifer matrix. As a consequence of the relatively large sizes of the lenses and the reduced heterogeneity in the aquifer material near Well D, Well D will respond in a fashion more typical of a well in an unconfined rather than a confined aquifer; whereas, wells located near Well B typically respond more like wells in a confined aquifer.

As supported by a discussion of hcw the pressure change is transmitted from Well B to the nearby wells, in Figure 36 the calculated

values of storage coefficients can vary from 0.000001 to 0.1 in a heterogeneous aquifer. In general, the lower values of storage coefficients occur when a highly transmissive, thin lens (or a series of lenses) intersects both the pumping and the observation wells. Higher values of storage coefficients occur when the aquifer material between the pumping and the observation well is more homogeneous and does not have continuous lenses that intersect both wells. Given these relationships, the trend in Table 23 is likely to be typical of heterogeneous aquifers. In short, for heterogeneous aquifers the likelihood of calculating low storage coefficient values decreases with increasing distance between the pumping and observation wells, because at greater distances there exists less likelihood that a thin lens of high conductivity material intersects the two wells.

3. Effect of the Duration of the Test

a. The Observed Trend

In Section V, the data from Aquifer Tests 1 and 3 indicate that the duration of the aquifer test affects the values of transmissivity and storage coefficient. The results in Tables 12 and 17 show that as the duration of the aquifer tests increased, the average values for transmissivity and storage coefficient decrease and increase, respectively. The data also shows that the variability among the transmissivities and storage coefficients decreased as the duration of the aquifer tests increased.

Because the duration of an aquifer test may affect the calculated values of transmissivities and storage coefficients, Figures 37 to 40 were constructed. Figures 37 to 40 include the transmissivities and storage coefficients calculated for the following data sets: (1) Aquifer Test 1 at times 2,000; 10,000; 50,000; and 100,000 seconds; (2) Aquifer Test 3 at times 2,000; 10,000; 50,000; 100,000; and 250,000 seconds; and (3) selected small-scale aquifer tests at times equal to 20 percent and 100 percent of the duration of the test. The small-scale aquifer tests not included in the data set have a

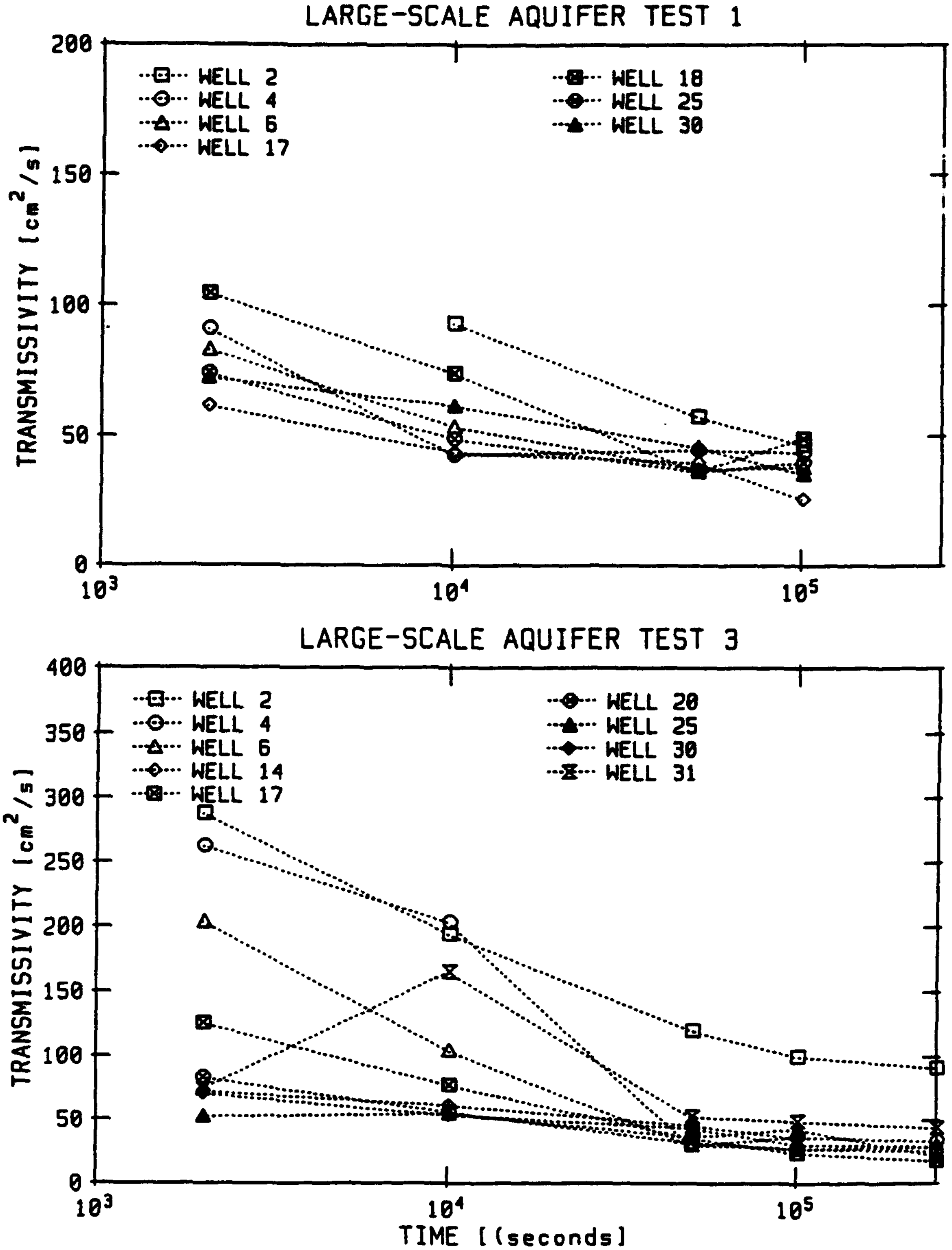


Figure 37. Transmissivities as a Function of Time for Large-Scale Aquifer Tests 1 and 3.

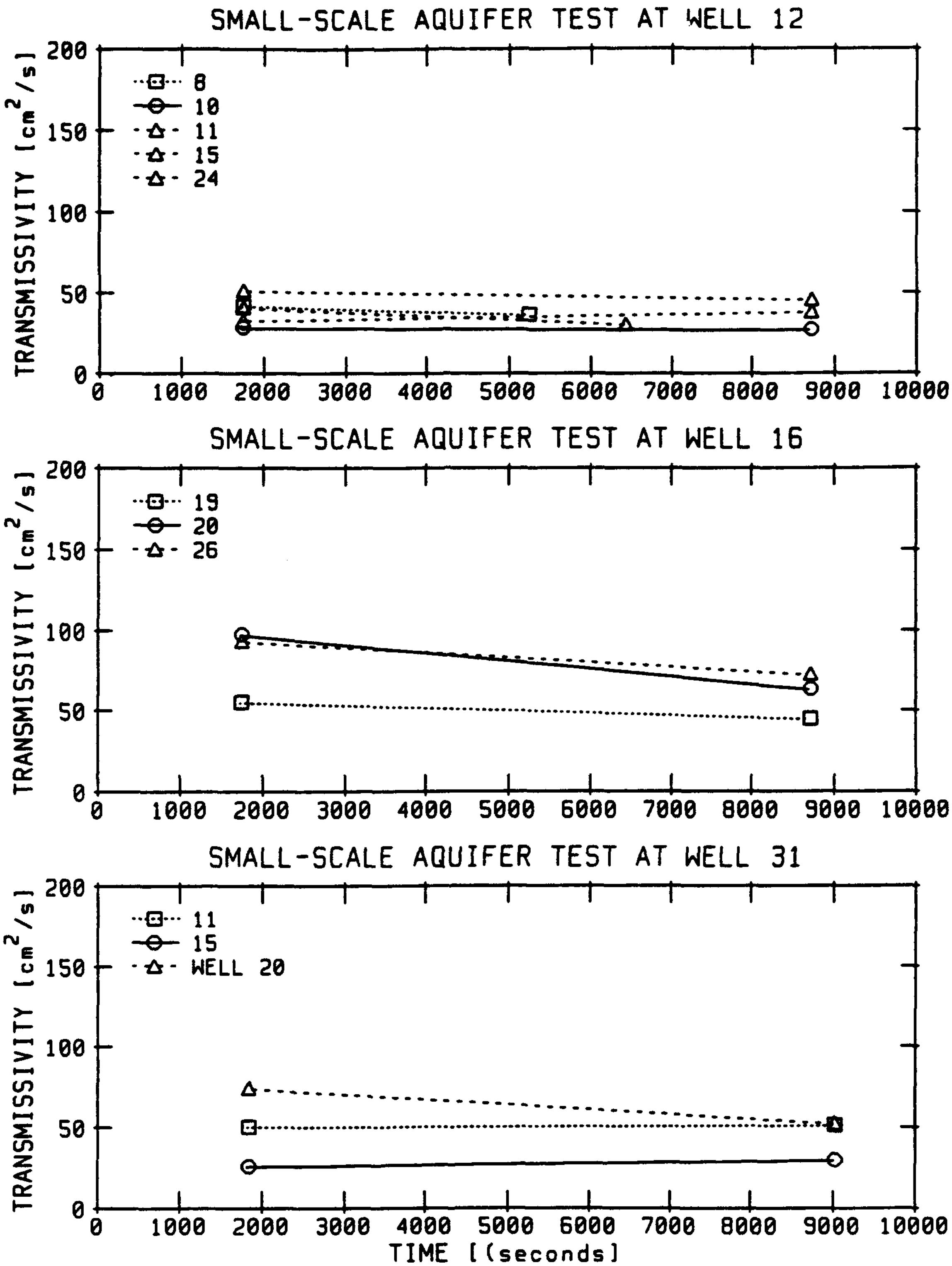


Figure 38. Transmissivities as a Function of Time for Small-Scale Aquifer Tests at Wells 12, 16, and 31.

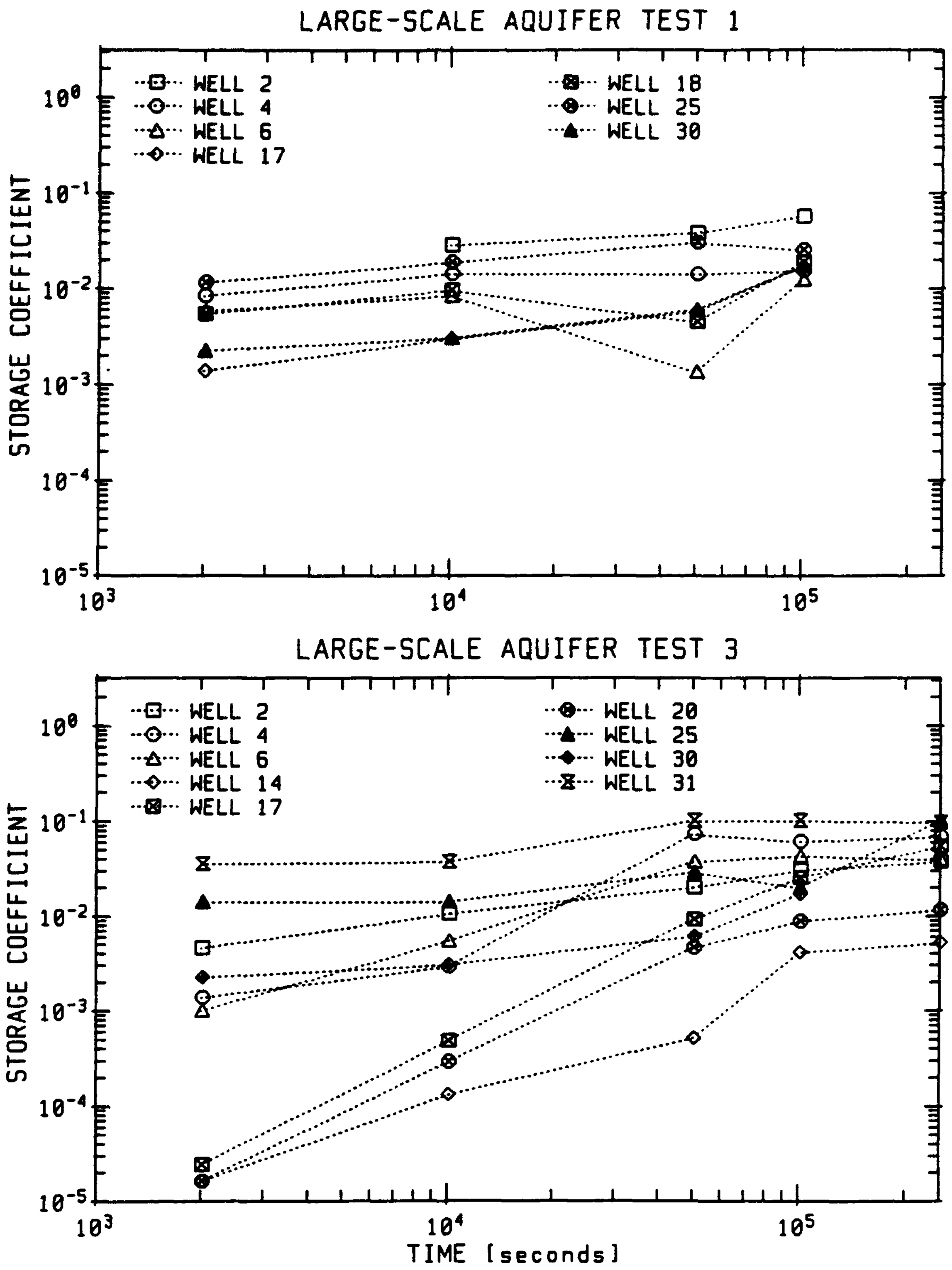


Figure 39. Storage Coefficients as a Function of Time for Large-Scale Aquifer Tests 1 and 3.

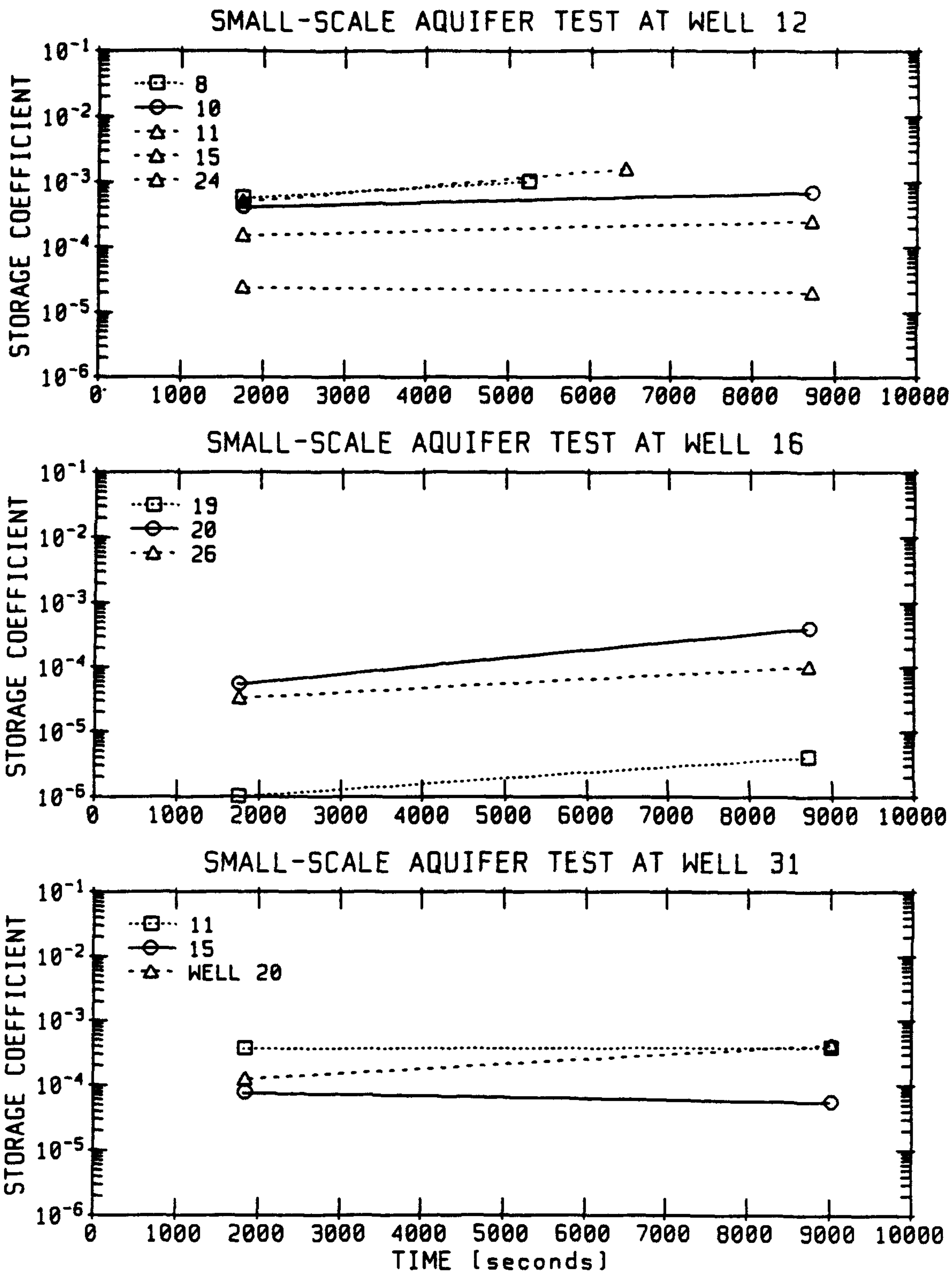


Figure 40. Storage Coefficients as a Function of Time for Small-Scale Aquifer Tests at Wells 12, 16, and 31.

maximum duration less than 5,000 seconds and/or have oscillations in the water table levels toward the end of the test.

Figures 37 to 40 indicate that the duration of the pumping tests affected the values for transmissivities and storage coefficients. Figures 37 and 38 show that for all the data sets except one, the transmissivities decreased over time. Figures 39 and 40 show that for all the data sets except one, the storage coefficients increased over time. Figures 37 to 40 indicate that an expanded duration from 2,000 to 10,000 seconds and from 2,000 to 250,000 seconds has a maximum affect on the calculated transmissivities and storage coefficients by factors of about two and ten, respectively.

b. Processes That Affect Temporal Differences

The trends in Figures 37 to 40 are affected by two processes. The first process is crossflow. Crossflows should produce the observed trend; the transmissivity and the storage coefficient decreases and increases, respectively, over time. The second process is the expansion of the cone-of-depression. The continued expansion of the cone-of-depression may or may not continue to produce the observed trend.

As discussed previously in this section and in Section V, the changes observed in the calculated transmissivities and storage coefficients during an aquifer test can be attributed to how an aquifer responds to stress. When an aquifer is stressed, the initial pressure response is first transmitted into and through the zones of high diffusivity. Initially, hydraulic pressure in a well will more closely represent the pressure in intersected zones of high diffusivities rather than the averaged pressure in the aquifer at the well location. Consequently, an analysis of the well data, at the beginning of pumping, will lead to estimates of transmissivities and storage coefficients more representative of the zones of high diffusivity rather than of the total thickness of the aquifer.

Because the pressure gradients between the zones of high and low diffusivity dissipate over time, the hydraulic pressure in the well

will more closely represent the pressure in the total aquifer at late times more than early times. Consequently, an analysis of the well data will lead to estimates of transmissivity and storage coefficients more representative of the total aquifer at late times more than early times.

As explained in Section III, the hydraulic properties calculated with the Theis equation represent a weighted average of aquifer materials near the observation well and aquifer materials enclosed by the cone-of-depression. As the cone-of-depression expands, aquifer materials at greater distances affect the rate of drawdown in the observation well. The potential importance of this effect can be illustrated with Figure 41. Figure 41 shows an aerial view of a fictitious heterogeneous aquifer in which the transmissivity is a function of radial distance from Well A.

As Well A is pumped, the front of the cone-of-depression will advance at different rates through the different regions of hydraulic conductivity. If Well B is monitored, then its water level will fall at a greater rate during the advancement of the cone-of-depression through the K_4 region than the K_1 region. Consequently, the hydraulic properties of the aquifer calculated based on the water table record at Well B will be dependent on the duration of the test. With regard to the concepts in Figure 41, it is possible to picture a pump test in which over time the cone-of-depression advances through an area of low transmissivity into an area of high transmissivity. In such an instance, the analysis of the drawdown data should indicate a trend toward higher transmissivity values with increases in the duration of the test. Similarly, it is possible to envision a pump test in which over time the cone-of-depression advances through an area of high transmissivity into an area of low transmissivity. In such an instance, the analysis of the drawdown data should indicate a trend toward lower transmissivity values with increases in the duration of the test. In the real world, however, it is difficult to picture geological structures that would create such well behavior radially symmetrical patterns in hydraulic conductivity patterns as shown in Figure 41. As a result of the complex heterogeneities found in real aquifers, one should expect instances where

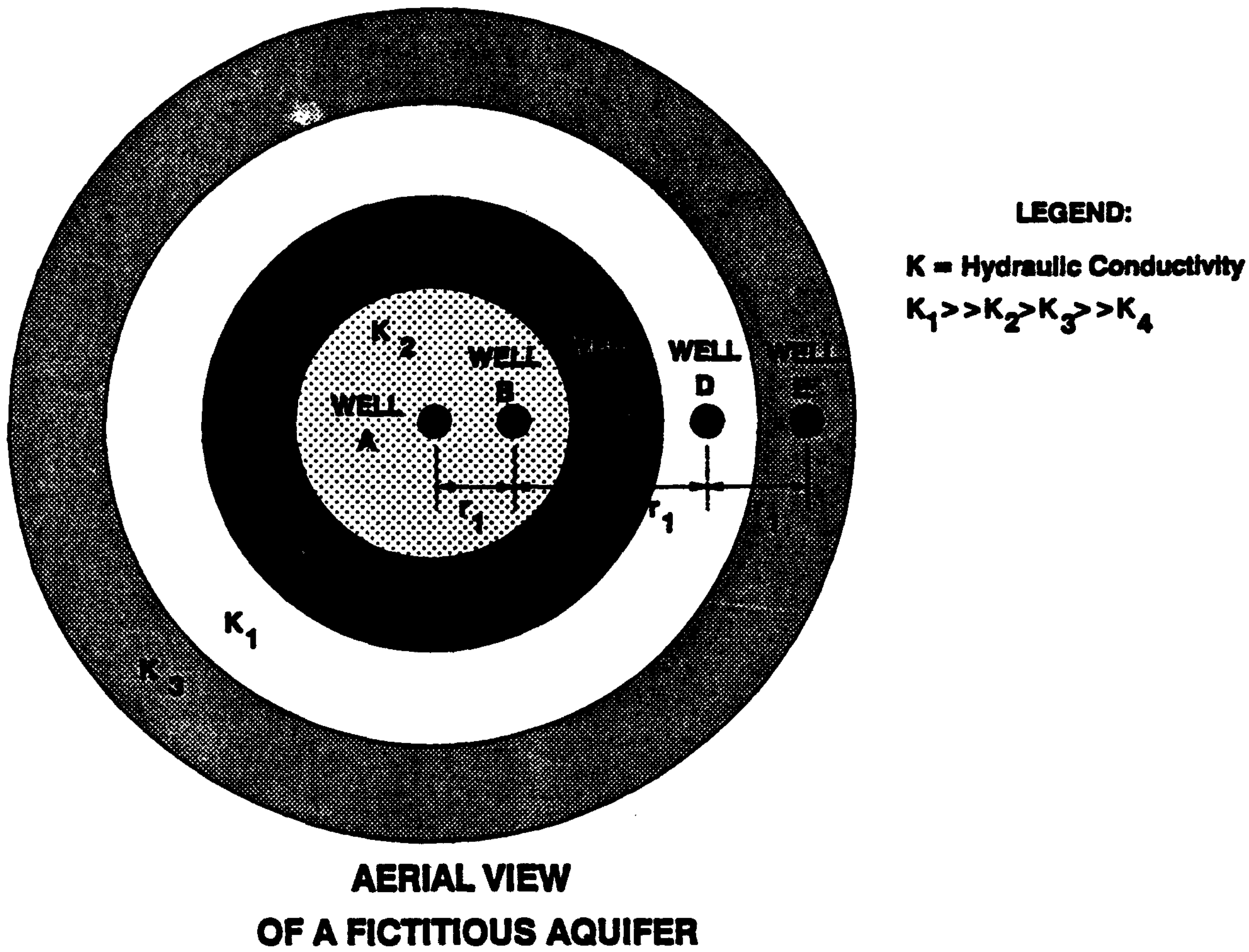


Figure 41. An Aerial View of a Fictitious Heterogeneous Aquifer.

no trend exists between transmissivity values and the duration of the pump test.

C. COMPARISON OF THEIS AND COOPER-JACOB TRANSMISSIVITIES

The hydraulic values determined from the Theis equation represent a weighted average between the local aquifer material near the pumping and observation wells, and the more distant aquifer material that resides within the cone-of-depression. The Cooper-Jacob straight-line method leads to hydraulic properties that are calculated based on the effects that the more distant aquifer materials have on the response of a well. Whereas the Theis-based hydraulic properties are calculated based on a match of total drawdown over time, the Cooper-Jacob based hydraulic properties are calculated based on a match of the slope of the time-drawdown curve at latter times. Because of the potential difference between the two methods, Figure 42 was constructed to compare the two methods.

Figure 42 was constructed from the data from Aquifer Test 1, Aquifer Test 2, and the small-scale aquifer test in Section V. Figure 42 shows that a good correlation exists between Theis-based and Cooper-Jacob based transmissivity. Most of the comparisons show that the two estimates differ by a factor less than 1.4, and for all of the comparisons except one, the two estimates differ by a factor less than 2.0.

D. TRANSMISSIVITY PATTERNS DERIVED FROM THE AQUIFER TESTS

1. Spatial Trends

The drawdown patterns observed in Aquifer Test 1 (see Figure 15) and Aquifer Test 3 (see Figure 26) show an asymmetrical response to the pumping well during the pumping tests. During the early periods of the pumping tests, the cone-of-depression penetrated further into the western than the eastern region. During the intermediate periods of the pumping tests, the advancement of the cone-of-depression stopped in the western region but continued in the eastern region. By the latter part of the

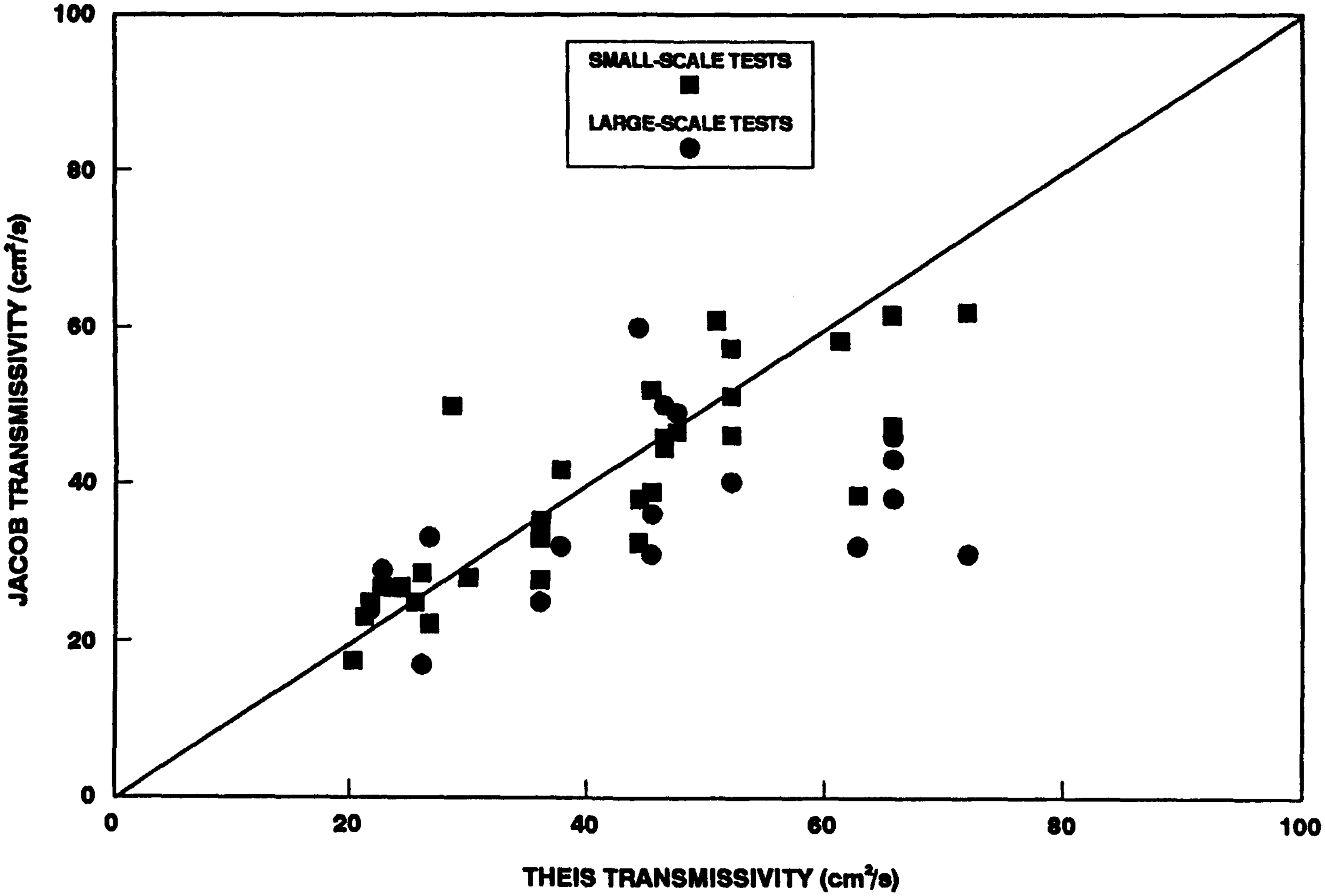


Figure 42. Comparison of the Theis and Cooper-Jacob Transmissivities.

pumping tests, the cone-of-depression had reversed the earlier drawdown pattern with the greatest drawdowns existing in the eastern region.

Overall, the drawdown pattern during Aquifer Tests 1 and 3 indicates that the aquifer has a large-scale trend in its structure: the western region has zones of considerably higher diffusivity than the eastern region. The results of the WELTEST analysis of Aquifer Test 2 and the Cooper-Jacob analysis of Aquifer Tests 1 and 3 indicate that the higher transmissivities lie in the western region of the well network.

2. Regional Averages

For Aquifer Tests 1 and 3, transmissivities were calculated for 27 wells. For Aquifer Test 2, transmissivities were calculated for 24 wells. Table 24 shows the average value and the standard deviation of the transmissivities for Aquifer Tests 1 and 3. In order to compare the results of all three aquifer tests, Table 24 shows the average value and the standard deviation of the transmissivities for the three aquifer tests at the same 23 well locations.

Table 24 indicates that the results of the aquifer tests are very similar. Attempts to evaluate the potential difference among the aquifer tests have been stymied because none of the transmissivities data sets are normally distributed. The Kolmorgorov-Smirnov method (Liffiefors, 1967) was used to check for normality. The lack of normality in the data sets precludes a rigorous application of confidence limits. Based on the available information and the results in Table 24, the regional averaged transmissivity in the interior of the well network is between 30 and 40 cm^2/s.

TABLE 24. THE ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR TRANSMISSIVITIES (cm^2/s) AQUIFER TESTS 1, 2, AND 3

	24 Wells			27 Wells	
	AT1	AT2	AT3	AT1	AT3
Arithmetic Mean	36.7	31.3	32.7	37.6	33.5
Standard Deviation	7.5	9.4	12.9	8.2	13.0

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SECTION VII

TRANSMISSIVITIES FROM SINGLE-WELL TESTS

A. OBJECTIVES

Single-well tests include pumping or injecting water at a designated well, monitoring the water table level in the designated well, and applying well equations to the test data to estimate the hydraulic properties of the aquifer. Traditionally, single-well tests have been used only to determine transmissivity values. Storage coefficients can theoretically be calculated from single-well tests; however, calculated storage coefficients are very sensitive to several uncertain properties of the well. These properties include, but are not limited to, the effective radius of the well, the skin effect produced during the well installation, and the storage capacity of the well. For the purpose of this project, the data from single-well tests will be used only for estimating transmissivity values.

With respect to characterizing transmissivity variability, single-well tests have several potential advantages over aquifer tests. These potential advantages include: (1) only one well is required for each test; (2) the test need last only long enough to produce adequate drawdown in the pumped well; and (3) the test can be designed to minimize the cone-of-depression and therefore transmissivity calculations can be performed for a relatively small volume of aquifer material.

Because of the potential advantages of single-well tests for characterization of an aquifer transmissivity field, a series of single-well tests were performed from April 1989 to July 1989 to accomplish the objectives listed in Table 25.

TABLE 25. OBJECTIVES FOR THE SINGLE-WELL TESTS

1. Determine the Average Values of Transmissivity at the CAFB Test Site
2. Develop a Method for Optimizing the Design of Single-Well Tests
3. Determine the Importance of the Skin Effect to Single-Well Tests

TABLE 25. OBJECTIVES FOR THE SINGLE-WELL TESTS (CONCLUDED)

4. Develop Simple Method for Data Analysis

5. Determine the Appropriateness of the Thiem Equation and the Cooper-Jacob Approximation for Single-Well Tests

6. Evaluate the Usefulness of Single-Well Tests to Characterize the Aquifer's Heterogeneity

7. Develop a Cost-Effective Method for Conducting and Analyzing Single-Well Tests

B. GENERAL APPROACH

Table 26 lists the single-well tests conducted at the test site. For each series cf tests, all 37 wells were included. The slug tests and the "2-minute" tests were conducted to investigate whether tests with small volumes of displaced water could provide reliable estimates of transmissivity. The injection tests were conducted to maximize the saturated thickness of the aquifer. The tests with different pumping rates were conducted to determine the effect of different pumping rates on the calculated transmissivities.

TABLE 26. SUMMARY OF THE SINGLE-WELL TESTS CONDUCTED AT CAFB

Type of Single-Well Test	Date
1. Falling-Head Slug Tests Slug tests had a displacement of 23 liters	4/89
2. 2-Minute 34 L/min Pump Tests	4/89
3. Injection Tests at 22 L/min	4/89
4. Pump Tests at Multiple Rates Multiple rates included the following three targeted pumping rates: (a) 15 L/min; (b) 30 L/min; (c) 60 L/min	6-7/89

Two important tasks associated with single-well tests are maintaining a constant pumping rate and collecting accurate drawdown data. For all of the tests, a positive displacement pump was used and the pumping rate was measured at least twice during each test. For each single-well test,

continuous measurements of drawdown were measured by Druck pressure transducers and recorded by Telog data-logging systems. The Druck transducers are accurate to within 0.3 cm. The Telog data-logging systems were used to record the drawdown measurements at 1-second intervals. No manually measured drawdown values were used in the data analysis.

All of the data analysis was performed interactively with one of three computer programs. The first, developed by Thompson (1987), was used to analyze the slug test data. The second was written by TVA to plot the time-drawdown data and to calculate the slope of selected segments of the data. The program permits the slope to be calculated either by fitting a straight-line through the end points or by performing a linear regression between the end points. The calculated slope is required to estimate the transmissivity from the Cooper-Jacob straight-line method. The third was written by TVA to solve the Thiem equation.

C. DESCRIPTION OF THE SINGLE-WELL TESTS

1. Slug Tests

On April 18, 1989, falling-head slug tests were performed in all 37 wells. Each test was performed using the following three-step procedure. First, a Druck transducer was placed approximately 2 meters beneath the water table and the Telog data logger was set to sample at 1-second intervals. Second, a large funnel was placed on top of the well and water was poured into the well from a 23-liter large-mouth jug. Finally, the time-drawdown data was visually displayed and then downloaded to a floppy disk. Each of the time-drawdown data sets was analyzed by designating the point of greatest build-up as the starting time and by applying the program by Thompson (1987).

The 23-liter volume is enough to fill 11.5 meters of 5.02-PVC well casing. Given a saturated thickness of 7.5 meters for the aquifer, the 23 liters is about 1.5 well casings. The 23-liter volume was poured into the well over a 10-15 second interval. No problems with overflows occurred during the tests. If the 23 liters move uniformly from the

well, the injected volume will displace water at a radial distance of 6.1 cm from the well casing based on an aquifer porosity of 0.32.

2. Short-Duration L/min Pump Tests

On 19 April 1989, short-duration pump tests were performed for all 37 wells. The targeted rate for the pumping was 34 L/min. The targeted duration for the test was 2 minutes. During the test, the pumping rate was checked by measuring the time required for the discharge to fill a 23-liter bucket. For each test, approximately 5 minutes was allowed for the water table to recover before the transducer data was downloaded to a floppy disk. When the pumping was stopped, a check-valve was closed to prevent pumped water from returning to the well.

The amount of water pumped for each test was about 64 liters. The 64-liter volume is enough to fill 20 meters of 5.02-PVC well casing. Given a saturated thickness of 7.5 meters for the aquifer and uniform movement of the 64 liters from the aquifer, the pumped volume will displace water at a radial distance of 9.6 cm from the well casing based on an aquifer porosity of 0.32.

3. Injection Tests at 22 L/min

From 20 April 1989, to 28 April 1989, injection tests were performed at all 37 wells. The tests were conducted by pumping water from a production well and into the test well. The production wells were selected to minimize the possible interference at the test well. The production wells had high specific yields (e.g., Wells 28, 2, 27, and 9) and locations that were at least 20 meters from the test wells. The water was injected into each well at a distance of about 1 meter from the top of the well and permitted to fall the remainder of the distance.

At the start and end of each test, the discharge from the production well was measured with a 23-liter bucket and a stopwatch. Each test lasted approximately 45 minutes. During the tests, measurements of the vertical discharge profile were made with an electromagnetic borehole flowmeter (Section 9). Throughout the test, the flowmeter was

also used to check the flowrate at designated intervals in the well. After each injection test, about 10 minutes of recovery data was recorded.

4. Pump Tests at Multiple Rates

Between 13 June 1989, and 28 July 1989, a series of pump tests were conducted to collect time-drawdown data for all 37 wells at targeted high (60 L/min), moderate (30 L/min), and low (15 L/min) pumping rates. Because of the variability in the transmissivities at each well location, pumping rates varied at some wells. In areas of low transmissivity, the highest pumping rates were lowered; and in areas of high transmissivity the pumping ranges were raised somewhat. Each pump test included a 20-minute pumping period and a 10-minute recovery period.

A total of 115 successful pump tests were conducted at the 37 wells. At least two successful tests were conducted at each well except for Well 1. The purpose of these tests was to determine whether the pumping rate affected the calculated transmissivities. During the 5-week span over which the pumping tests were conducted, the averaged water table elevation across the well networks dropped 0.25 meters because of naturally occurring seasonal fluctuations. This decrease is approximately 3 percent of the saturated thickness of the aquifer and should have a negligible effect on the overall trends.

D. SINGLE-WELL TEST RESULTS

1. Tabulated Results

Table 27 shows the tabulated results for the five single-well tests and provides the results for Aquifer Tests 1 and 2 for comparison. The slug test transmissivities were calculated using the program from Thompson (1987), and the other single-well test transmissivities were calculated using the Cooper-Jacob straight-line method. Table 28 provides a summary of a statistical analysis of the data in Table 27.

TABLE 27. TRANSMISSIVITIES (cm^2/s) CALCULATED FROM SINGLE-WELL AND AQUIFER TESTS

Well	Slug Test	Short Dur. Pump Test	Inject. Test	Pump at Low Rate*	Pump at High Rate**	Aquif. Test 1	Aquif. Test 3
1	.6	.8	46.3	22.0	22.0	57.1	62.4
2	.6	10.0	108.8	516.0	17.0	50.4	74.8
3	2.6	31.6	110.8	107.0	71.0	56.5	56.2
4	1.7	1.0	10.3	4.0	45.0	41.8	32.4
5	5.1	7.9	29.0	87.0	65.0	33.7	19.6
6	5.1	10.0	18.4	89.0	26.0	48.6	26.9
7	.9	1.6	16.2	67.0	17.0	42.8	36.1
8	.7	.1	2.7	2.0	15.0	27.1	30.2
9	2.6	2.5	91.1	88.0	21.0	34.8	37.9
10	2.6	3.2	11.7	33.0	16.0	36.1	23.7
11	1.7	2.0	23.7	66.0	48.0	38.1	26.1
12	3.4	.5	50.6	16.5	56.0	28.6	27.0
13	5.1	12.6	17.7	70.0	41.0	32.6	25.5
14	3.4	4.0	15.7	43.0	70.0	36.1	29.3
15	.9	2.0	6.9	39.0	63.0	28.6	27.5
16	1.7	12.6	25.8	150.0	71.0	27.4	34.1
17	.8	.2	7.0	19.0	37.0	32.2	17.0
18	2.6	2.5	36.7	286.0	59.0	46.4	45.8
19	1.7	2.5	26.9	241.0	32.0	34.3	26.5
20	.5	.2	8.0	28.0	38.0	28.1	23.6
21	5.1	10.0	13.9	44.0	23.0	39.4	27.8
22	6.0	4.0	24.8	24.0	15.0	-	-
23	6.0	4.0	8.4	10.0	26.0	-	-
24	5.1	12.6	21.4	36.0	15.0	38.1	25.3
25	5.1	20.0	19.6	40.0	33.0	36.7	25.3
26	5.1	39.8	48.0	111.0	22.0	36.1	33.2
27	5.1	10.0	22.5	11.0	30.0	-	-
28	5.1	31.6	98.5	130.0	33.0	-	-
29	5.1	20.0	58.8	69.0	14.0	-	-
30	4.3	5.0	31.0	58.0	44.0	42.6	35.7
31	6.0	7.9	26.0	46.0	55.0	34.3	31.9
32	6.0	5.0	12.9	37.0	46.0	34.8	34.2
33	6.0	39.8	42.9	47.0	50.0	-	-
34	3.4	.3	.8	1.0	3.0	-	-
35	3.4	5.0	12.3	24.0	12.0	-	-
36	1.7	2.5	6.4	4.0	74.0	-	-
37	6.0	47.9	98.9	123.0	66.0	-	-

* most of the low rates are between 10 and 20 L/min

** most of the high rates are between 55 and 80 L/min

TABLE 28. SUMMARY OF THE STATISTICAL ANALYSIS OF THE SINGLE-WELL AND AQUIFER TESTS RESULTS

	Transmissivity (cm^2/s)					
	Arithmetic Values			Logarithmic Values		
Data Set	Mean	SD	KS	Mean	SD	KS
Slug test	3.5	2.0	0.80	2.7	2.3	0.69
Short Dur. Pump Test	10.1	12.6	0.66	4.1	5.0	0.48
Inject. Test	32.7	31.7	0.23	21.1	2.9	0.059
Pump Test (Low Rate)	75.5	97.0	0.28	39.3	3.8	0.127
Pump Test (High Rate)	37.6	20.3	0.28	31.2	2.0	0.187
Aquifer Test 1	36.7	7.5	0.38			
Aquifer Test 3	32.7	12.9	0.26			

SD = standard deviation
KS = value calculated to check normality based on Kolmorgorov-Smirnov Test (Liffiefors, 1967). Normality can't be rejected at 99% and 95% confidence limits if KS is less than 0.169 and 0.145, respectively.

2. General Trends and Correlations

The results of the Kolmorgorov-Smirnov test in Table 28 indicate that none of the transmissivity distributions are normally disturbed. However, the distributions for the logarithm of the transmissivities for the injection tests and the low-rate pumping tests appear to be normally distributed. This result supports the results of Freeze (1975) and Law (1944), who show that in many instances the assumption of log-normally distributed transmissivities is valid.

Figure 43 compares the arithmetic and geometric averages of the different transmissivity data sets and the arithmetic average of Aquifer Tests 1 and 3. The confidence limits shown in Figure 43 are based on the assumption of a normal-distribution for the transmissivity field which does not exist; hence, the confidence limits are not accurate. However, the confidence limits are shown because they provide a relative qualitative measure of the uncertainty associated with each average.

The different transmissivities distribution obtained from the different single-well tests indicate that the design of the single-well tests has an impact on the calculated value of transmissivity. Based solely on the information in Table 28, it would appear that the pumping

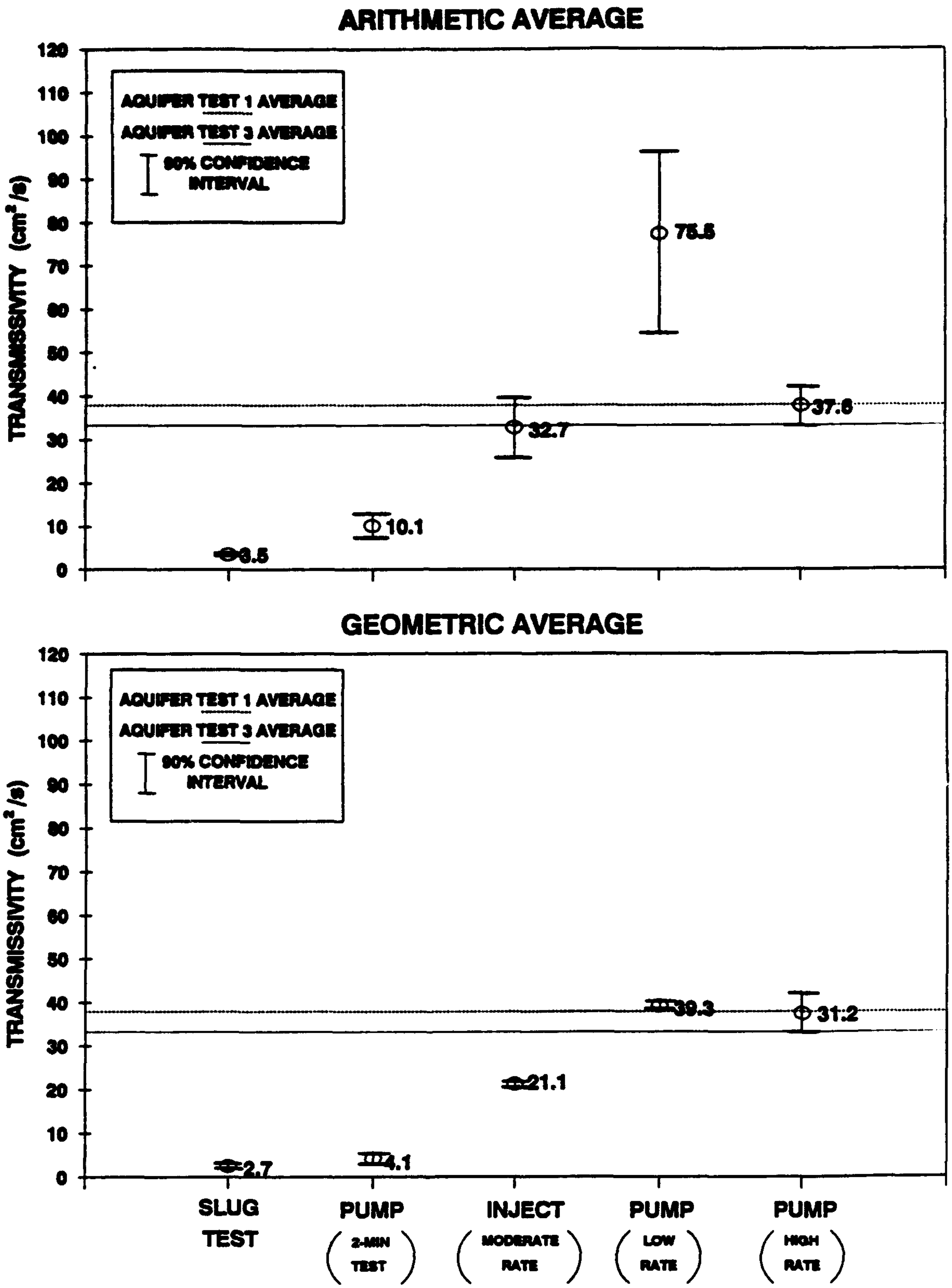

Figure 43. The Arithmetic and Geometric Averages for the Single-Well and the Aquifer Tests 1 and 3.

rate and the duration of a test, which affects the radius of influence of the cone-of-depression, are important considerations in the design of single-well pump tests.

Table 28 shows that the two single-well tests with the smallest radius of influence (i.e., the slug test and the short-duration pump test) have mean transmissivity values considerably less than the mean transmissivity values for the aquifer tests. Also shown in Table 28 is that the two single-well tests with the largest radius of influence (i.e., the high-rate pumping test and the injection tests) have mean transmissivity values that closely match the mean transmissivity for the aquifer tests.

A possible explanation for the low transmissivity values from the slug tests and the short-duration pump tests is a negative skin effect. A negative skin effect is a zone of low hydraulic conductivity near the well that is produced as a result of the well installation activities (see Section IV).

The good match between mean transmissivity values for the injection and high-rate pumping single-well tests and for the Aquifer Tests 1 and 3 probably occurred because of two reasons. First, the single-well tests were conducted at locations relatively symmetrical with respect to the pumping well used for the aquifer tests. Second, both types of single-well tests, with the relatively large radius of influences, produced time-drawdown curves whose change in the drawdown rate were more affected by the regional aquifers than the local aquifer properties near the well.

Besides its affect on the mean value of transmissivity, the importance of the pumping rate and the duration of single-well tests is reflected in the standard deviation of the transmissivity values. For the three single-well tests for which the skin effects have been ignored by the application of the Cooper-Jacob straight-line method, the standard deviation decreases with increases in the radius of influence. Table 28 shows that the lowest standard deviations are for the aquifer tests followed by the high-rate pumping tests, moderate-rate injection tests,

and then low-rate pumping tests. This trend occurs because the greater the radius of influence, the more reflective the time-drawdown curve will be of regional aquifer than local aquifer properties.

Figures 44 and 45 compare computed transmissivities in terms of well installation technique and test type. No obvious effects of the different well installation techniques on the calculated transmissivities is evident in the plots that include data from the three single-well tests with moderate to large radius of influences. The lack of any type of correlation based on well type is encouraging because it indicates that any effect that the different well installations has on the drawdown curve can be properly accounted for by disregarding the early drawdown data as is done with the Cooper-Jacob straight-line method.

In the bottom plot in Figure 45, a potential trend appears to exist in the comparison between the plotted transmissivity values between the short-duration pump tests and the slug tests. The plot shows that 10 of the 12 slug tests at the air percussion wells produce nearly the same value of transmissivity although at these same 10 wells, the short-duration pump tests produce transmissivities that were rather uniformly distributed over a transmissivity range of an order of magnitude. This trend indicates that slug tests may not provide even a relative qualitative estimate of the transmissivity when conducted in wells drilled by the air percussion method.

E. COOPER-JACOB AND COOPER-JACOB STRAIGHT-LINE TRANSMISSIVITIES

1. Appropriate Well Equations for Calculating Transmissivities

As shown in Section IV, the Thiem equation can be derived by applying the Cooper-Jacob equation to solve for the flow through two cylindrical areas at different radii from a well. Conversely, the Cooper-Jacob equation can be derived from the Thiem equation by assuming that the most distance radius of interest from the well is the radius of influence. The radius of influence represents the minimal distance at which the drawdown equals zero. If the radius of influence, as defined by Equation (22), is inserted into the Thiem equation as the radius of

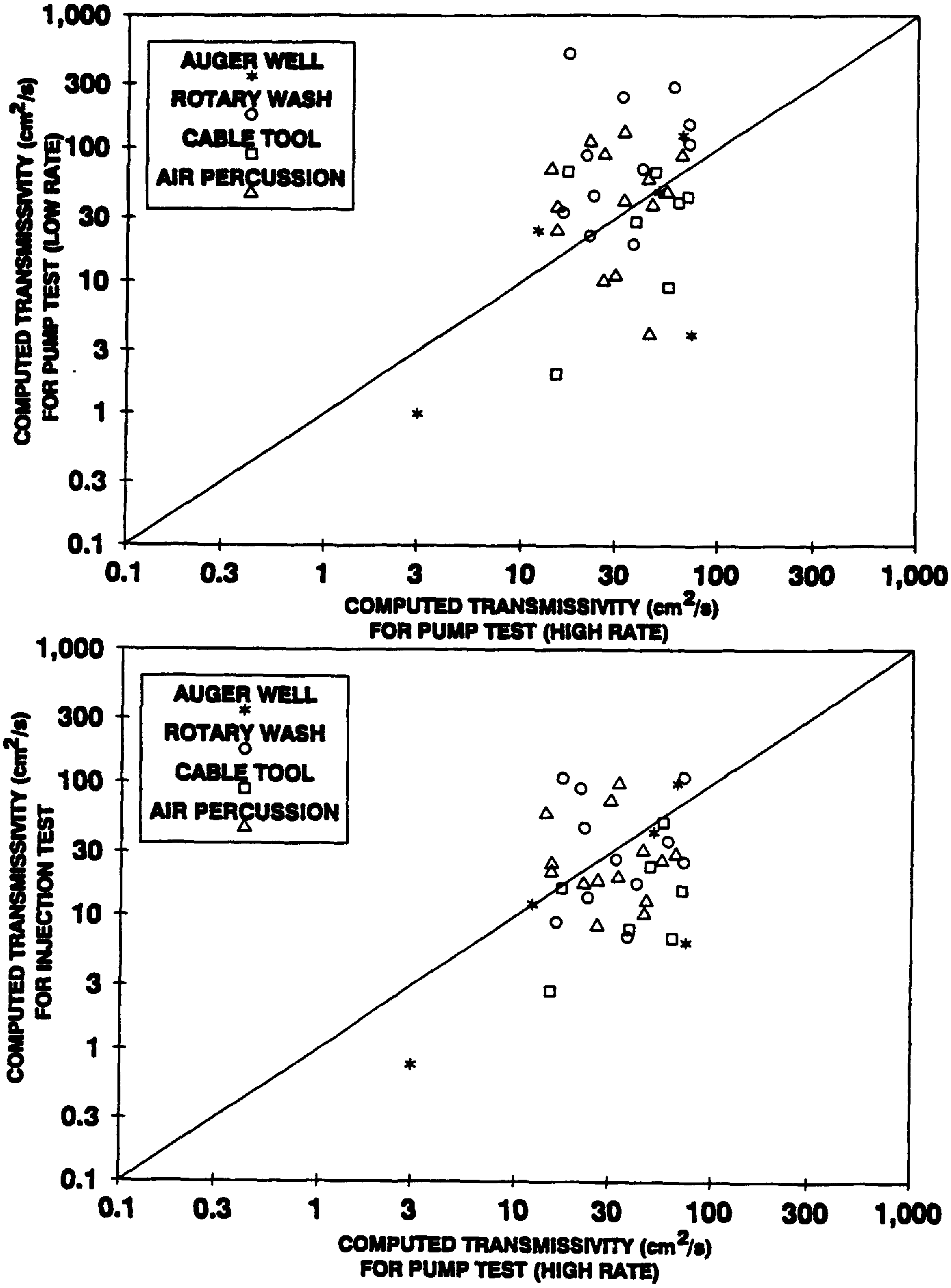

Figure 44. Comparisons Among the Results From the Injection, High-Rate Pumping, and Low-Rate Pumping Single-Well Tests.

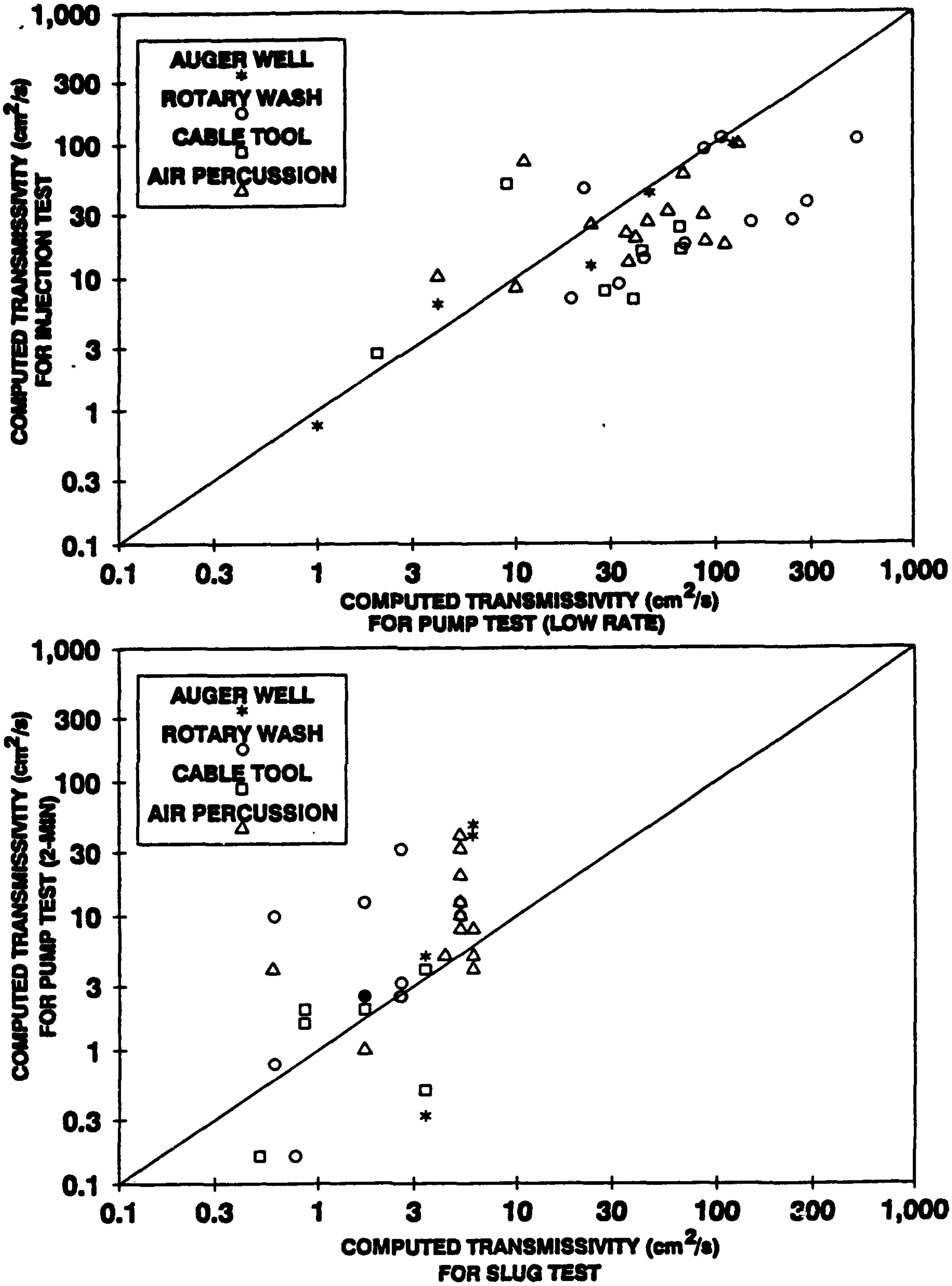

Figure 45. Comparison Between the Results of the Injection Test and the Low-Rate Test Results and Between the Results of the Slug Test and the Short-Duration Pump Tests.

greatest distance, see Equation (5), the Thiem equation simplifies to Equation (23), which is the Cooper-Jacob equation.

$$R = \sqrt{\frac{2.25Tt}{S}} \tag{22}$$

$$s(r,t) = \frac{Q}{4\pi T} \ln \frac{2.25Tt}{r^2 S} \tag{23}$$

Equation (23), or a slightly modified form, has been used by numerous researchers (Rehfeldt, et al., 1989; Hess, 1989; Boggs, et al., 1990; and Morin, 1988) to calculate transmissivities and/or hydraulic conductivities for individual layers in an aquifer. An important assumption in Equation (23) is that the aquifer material around and near the well is homogeneous. If a skin effect exists at the well then the total drawdown is a function of both the material in the disturbed zone and the aquifer, see Equation (18), and Equation (23) will not be valid for calculating the transmissivity of the natural aquifer material. The importance of the skin effect can be determined by comparing the value for K, the depth-averaged hydraulic conductivity, calculated from Equation (23) to form the Cooper-Jacob straight-line analysis.

Recall that the Cooper-Jacob equation (1946), and the Cooper-Jacob straight-line method are different ways to express the same mathematical relationships. An important similarity of the two equations is that both are valid only after enough time has elapsed to reduce u (see list of symbols) to less than 0.01. For an ideal well in a homogeneous aquifer, once u is less than 0.01, the drawdown should plot as a straight line against the logarithm of time. An important difference between the two equations is that only the Cooper-Jacob straight-line analysis requires the time-drawdown data be plotted and examined to determine whether they plot a straight line after u equal 0.01.

Of the 149 single-well pump tests conducted at the test site, the majority of the well responses did not plot a straight line until an elapsed time of about 1 minute. Most of the drawdown plots were similar to the features shown in Figure 46, which shows that a straight-line

slope does not occur until after approximately 1 minute. Based on the calculated transmissivities and storativities for the different well locations, the elapsed time to reduce the value of u below 0.01 is less than 10 seconds at most of the wells. The "1-minute" delay is attributed to skin effects and indicates that the Cooper-Jacob equation and the Cooper-Jacob straight-line analysis will provide different estimates for transmissivities.

The Cooper-Jacob straight-line analysis requires the geohydrologist to determine the most appropriate straight line through the data and use Equation (3) to calculate K. As shown in Figure 46, the skin effects can be avoided by simply calculating the straight-line slope after the first several hundred seconds of the pumping test. For the time-drawdown relationship shown in Figure 46, the Cooper-Jacob equation and the Cooper-Jacob straight-line analysis give transmissivities of 11 cm^2/s and 32 cm^2/s, respectively. For a well radius of 2.5 cm and a storage coefficient of 0.01, the value of u is less than 0.01 before 1 second for both estimates of transmissivity. However, Figure 46 shows that a straight-line relationship is achieved at 50 seconds instead of the expected 1 second. This difference indicates that a negative skin effect exists at the well. Consequently, in order to account for the skin effects the Cooper-Jacob straight-line analysis, and not the Cooper-Jacob equation, should be used to calculate transmissivities.

2. Analysis of 149 Pump Tests

One benefit of the Cooper-Jacob equation over the Cooper-Jacob straight-line analysis is that only one drawdown measurement is required. However, to use the Cooper-Jacob equation, one needs not only to assume no skin effects exists, but also a constant storage coefficient value for the aquifer. The results from Section V show that the storage coefficient values from the large- and small-scale aquifer tests vary five orders of magnitude. In order to investigate the usefulness and accuracy of the Cooper-Jacob equation as compared to the Cooper-Jacob straight-line method, both methods were used to calculate the transmissivities from 114 pump tests and 35 injection tests.

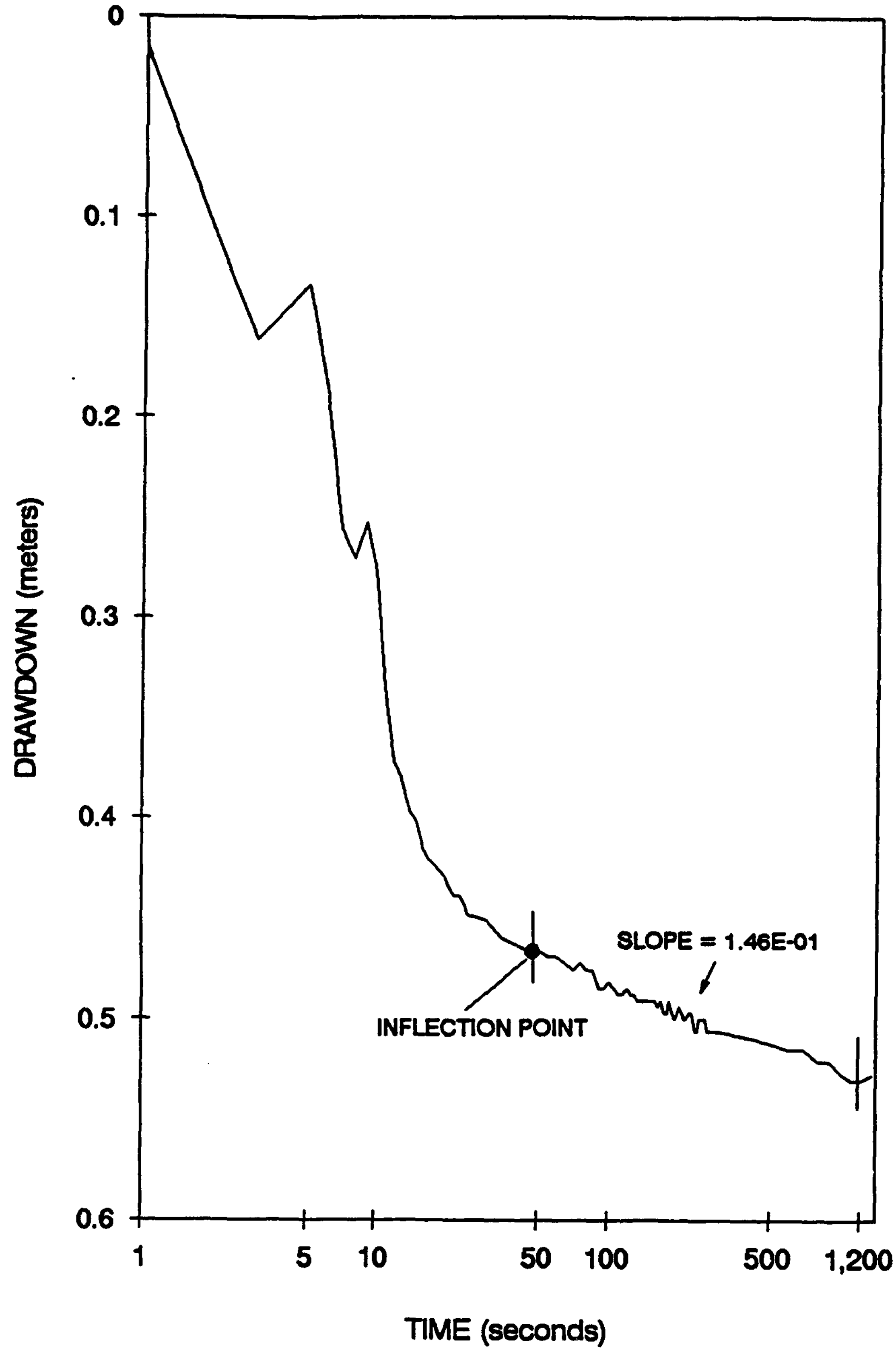

Figure 46. An Example Drawdown Curve (from Well 12) for the Single-Well Pump Tests.

The Cooper-Jacob straight-line analysis was applied to each set of drawdown data in the same manner as shown in Figure 46. For all of the tests, the slope was calculated after the inflection point. For some of the tests, total drawdown was greater than 10 percent of the aquifer thickness. For these tests, the Jacob correction factor (see Section III) was applied to the drawdown data before the slope was calculated. The solution to the Cooper-Jacob equation was solved by the program discussed in subsection B, General Approach. The Cooper-Jacob equation was applied to the time and drawdown values at the end of the pump test.

Figure 47 shows the distribution of the ratios for the transmissivities calculated by the Cooper-Jacob equation and by the Cooper-Jacob straight-line analysis for the pump tests. Table 29 summarizes the results of the pump tests.

TABLE 29. THE EFFECTS OF DIFFERENT STORAGE COEFFICIENT VALUES ON THE RATIO BETWEEN COOPER-JACOB EQUATION AND THE COOPER-JACOB STRAIGHT-LINE TRANSMISSIVITIES

	Pump Tests	Injection Tests
Number of Tests	115	35
Average Rate (L/min)	37	22
Average Inflection Time (seconds)	70	104
Average Drawdown at Inflection (m)	1.2	-0.28
Average Test Duration (seconds)	1340	2692
Average Total Drawdown (m)	1.4	-0.46
Average Transmissivity Based on the Cooper-Jacob Straight-Line Analysis (cm^2/s)	52.1	31.1
Average Transmissivity Based on Cooper-Jacob Equation (cm^2/s)		
Storage Coefficient = 0.1	6.7	14.4
Storage Coefficient = 0.00001	16.09	26.5

As shown in Figure 47 and Table 29, significant differences exists between the transmissivities calculated by applying the Cooper-Jacob equation and by applying the Cooper-Jacob straight-line analysis. The results show that the ratio of the transmissivities calculated from the

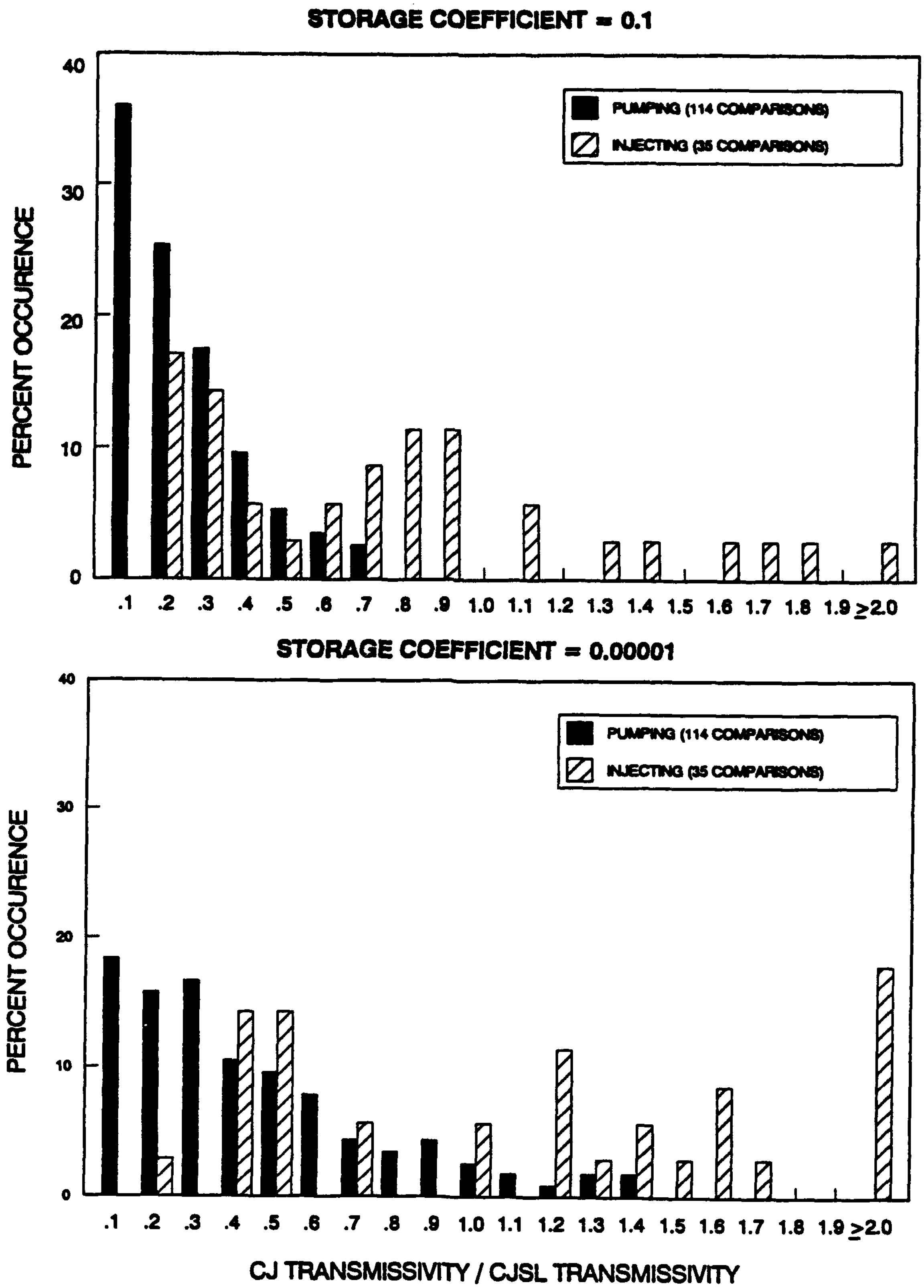

Figure 47. Comparison Between the Transmissivities Calculated by the Cooper-Jacob (CJ) and the Cooper-Jacob Straight Line (CJSL) Equations.

two methods is sensitive to the assumed storage coefficient and is affected by whether the water is withdrawn or injected during the pump tests. In general, comparisons indicate that the Cooper-Jacob equation can lead to order of magnitude errors in calculating transmissivities at the CAFB test site and, therefore, should not be used. Any benefits gained by reducing the field measurements to a single drawdown value is outweighed by the large uncertainties associated with applying the Cooper-Jacob equation when skin effects exist and the aquifer is heterogeneous.

One of the interesting aspects about Figure 47 is the difference in the distribution between the results of the pumping and the injection tests. The results in Figure 47 indicate that a significantly greater likelihood exists that the ratio between the transmissivities calculated from the Cooper-Jacob equation and the Cooper-Jacob straight-line analysis will be greater than one for an injection test rather than for a pumping test. A ratio greater than one indicates that the rate of build-up is greater at late times rather than at early times of the test. One explanation for this trend at some wells is that during the start of an injection test, the build-up of the water table is slowed by the lateral flow of water in the unsaturated zone.

F. THE DESIGN OF SINGLE-WELL PUMPING TEST

1. The Effects of Withdrawing or Injecting Water

The results in Figure 45 indicate that the direction of water flow during a single-well test may affect the calculated value of transmissivity. In order to investigate this possibility, Table 30 was created. Table 30 lists the values of transmissivities calculated for the same well from data taken during a single-well pump and injection test that had flowrates between 18 and 27 L/min. The results in Table 30 show that the injection tests produced consistently lower transmissivity values. This result is contrary to what is expected given that the saturated thickness of the aquifer was about 0.6 meters greater for the injection tests than for the pumping tests.

TABLE 30. TRANSMISSIVITIES (cm^2/s) CALCULATED AT THE SAME WELL BY INJECTION AND PUMPING TESTS WITH FLOW RATES NEAR 23 L/MIN

Well	Pumping	Injecting
6	89.0	18.4
8	2.0	2.7
14	43.0	15.7
23	10.0	8.4
26	111.0	48.0
33	47.0	42.9
34	1.0	0.8

The reason for the trend in Table 30 is not clear. The explanation for the apparent discrepancy is likely related to one of the following three differences in the test: (1) the injection test has a flow field that has a diverging flow field; the pumping test has a converging flow field; (2) less water per unit area is required to change the water table during the injection test than during the pumping test because of the hysteretic properties of the soils; and (3) during the injection test, the aquifer matrix is expanding and the water molecules are compressing because of increases in groundwater pressure; during the pumping tests, the aquifer matrix is compressing and the water is expanding because of decreases in groundwater pressure.

2. The Effect of Pumping Rate on the Calculated Transmissivity

As discussed in Sections III and IV, the transmissivity calculated by the Cooper-Jacob method is very sensitive to the material through which the cone-of-depression passes. Low pumping rates will keep the cone-of-depression close to the well whereas high pumping rates will spread the cone-of-depression from the well. If the hydraulic properties of the aquifer material change with distance from the well, then the calculated transmissivity, which reflects a weighted average of these properties, should change. By performing a series of single-well tests at different rates, one may determine whether the well is located in a zone of high or low transmissivity relative to the aquifer material around it.

In order to investigate the potential importance of the pumping well rate on the calculated transmissivity from single-well pump tests, single-well pump tests were conducted at every well except at Well 1 at different rates. Figure 48 shows an example (Well 7) of the type of drawdown results obtained from performing a series of pump tests at different rates at a single location. Figures 49 and 50 present the results of the 114 pump tests conducted at the 37 wells.

The test results show great variability among the results for the different tests. At some of the wells (2, 18, 19, 16, 28, 37, and 26), the transmissivities increased over an order of magnitude as the pumping rate increased. At other wells (4, 36, 8, and 34), the transmissivities increased over an order of magnitude. At about half of the wells, the transmissivities changed by less than a factor of 4.

An examination of the results indicate that a zone of relatively high transmissivity exists in the vicinity of Wells 2, 18, 19, 16, 28, 37, 26, 3, 6, and 9. Within this zone, higher pumping rates produce lower estimates of transmissivities. Wells located in material of low transmissivity (Wells 36, 24, 23, and 27), but not far from the area of the aquifer with high transmissivities, show a trend of higher transmissivities with higher pumping rates. Overall, the results indicate that the pumping rate can have a large effect on the calculated transmissivities for single-well tests, because higher pumping rates include flow from distant regions of different transmissivity.

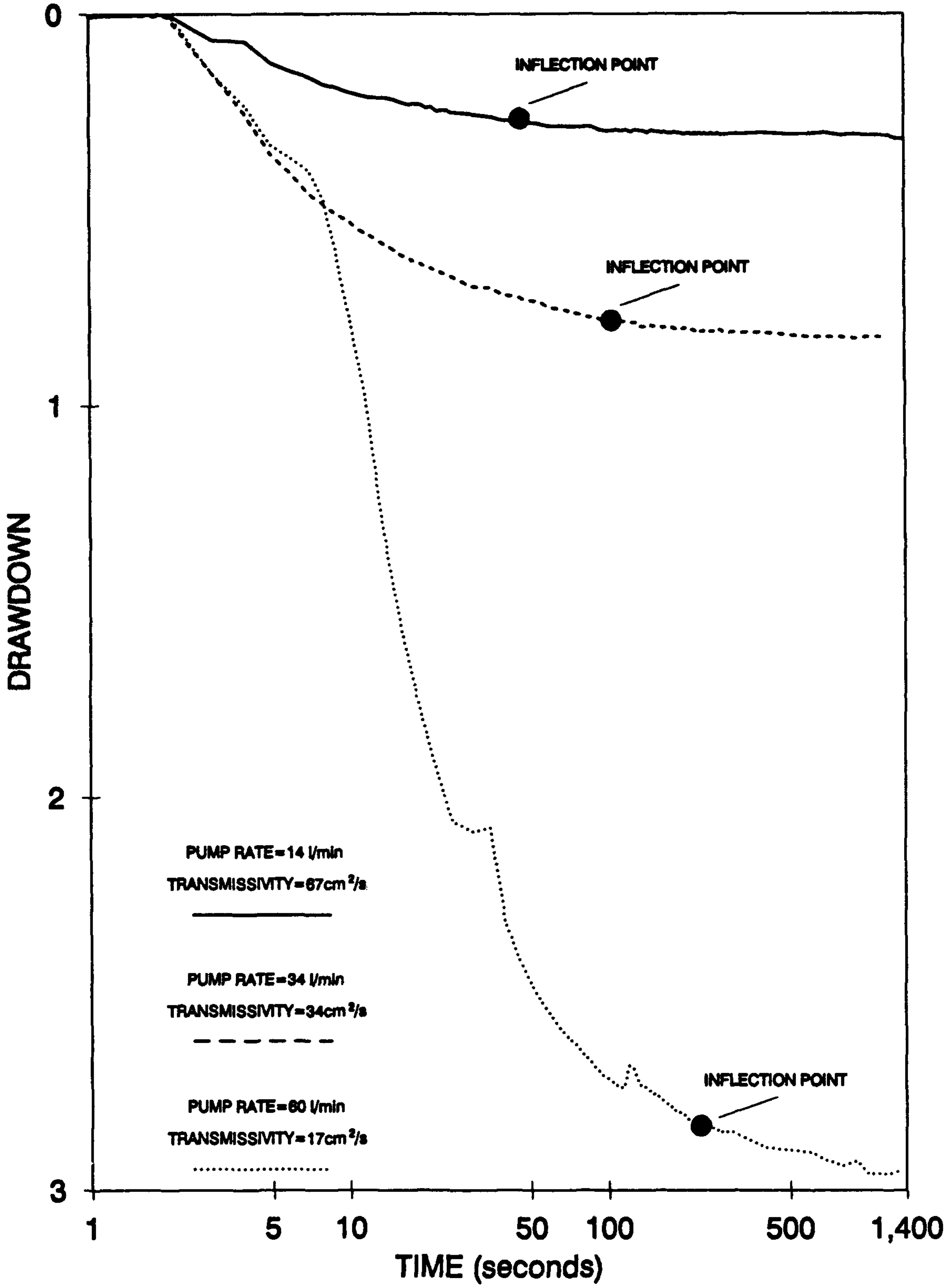

Figure 48. Drawdown Curves for the Multiple Pump Tests at Well 7.

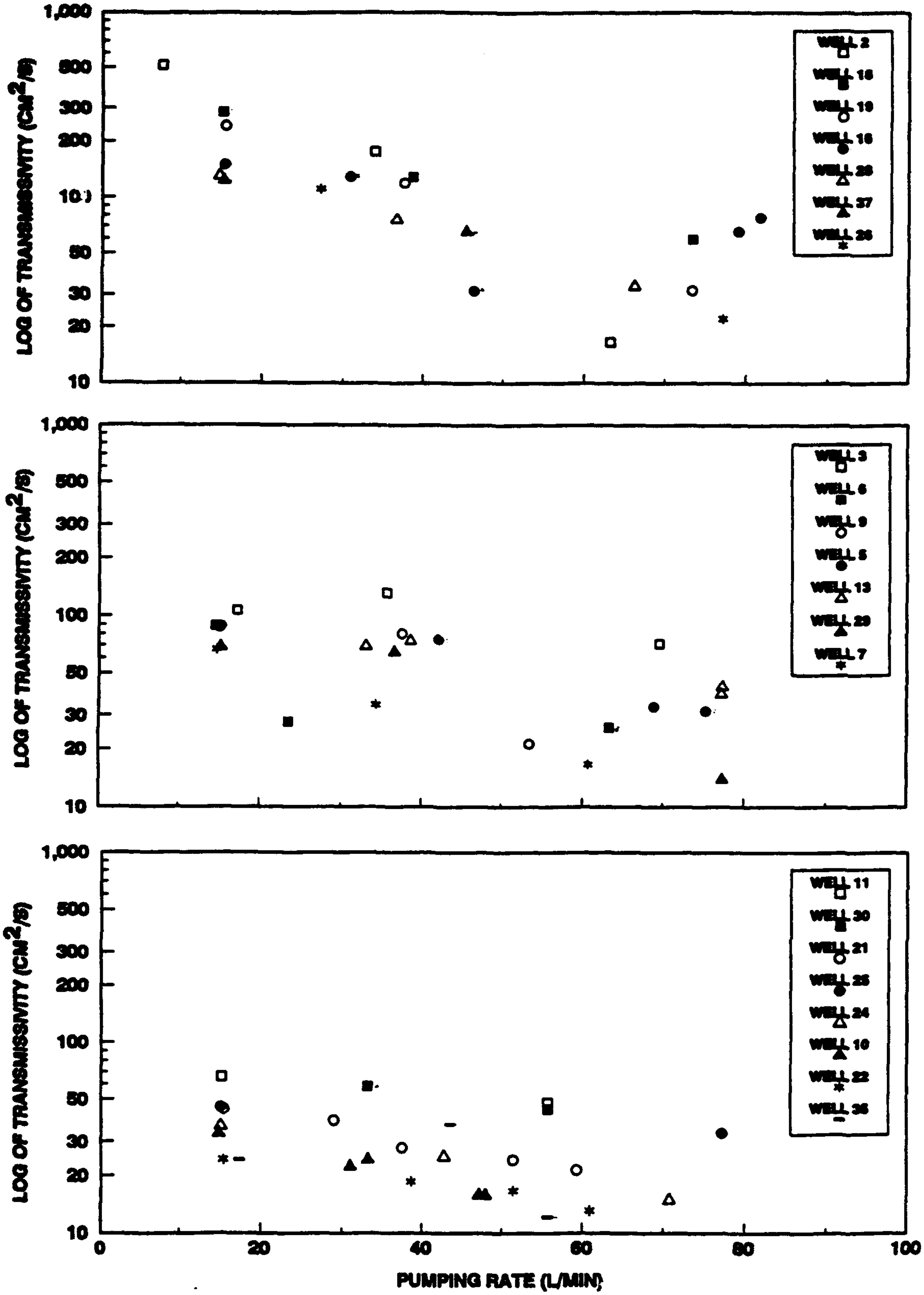

Figure 49. Calculated Transmissivities for Well Locations Where Transmissivity Decreased With Increases in the Pumping Rate.

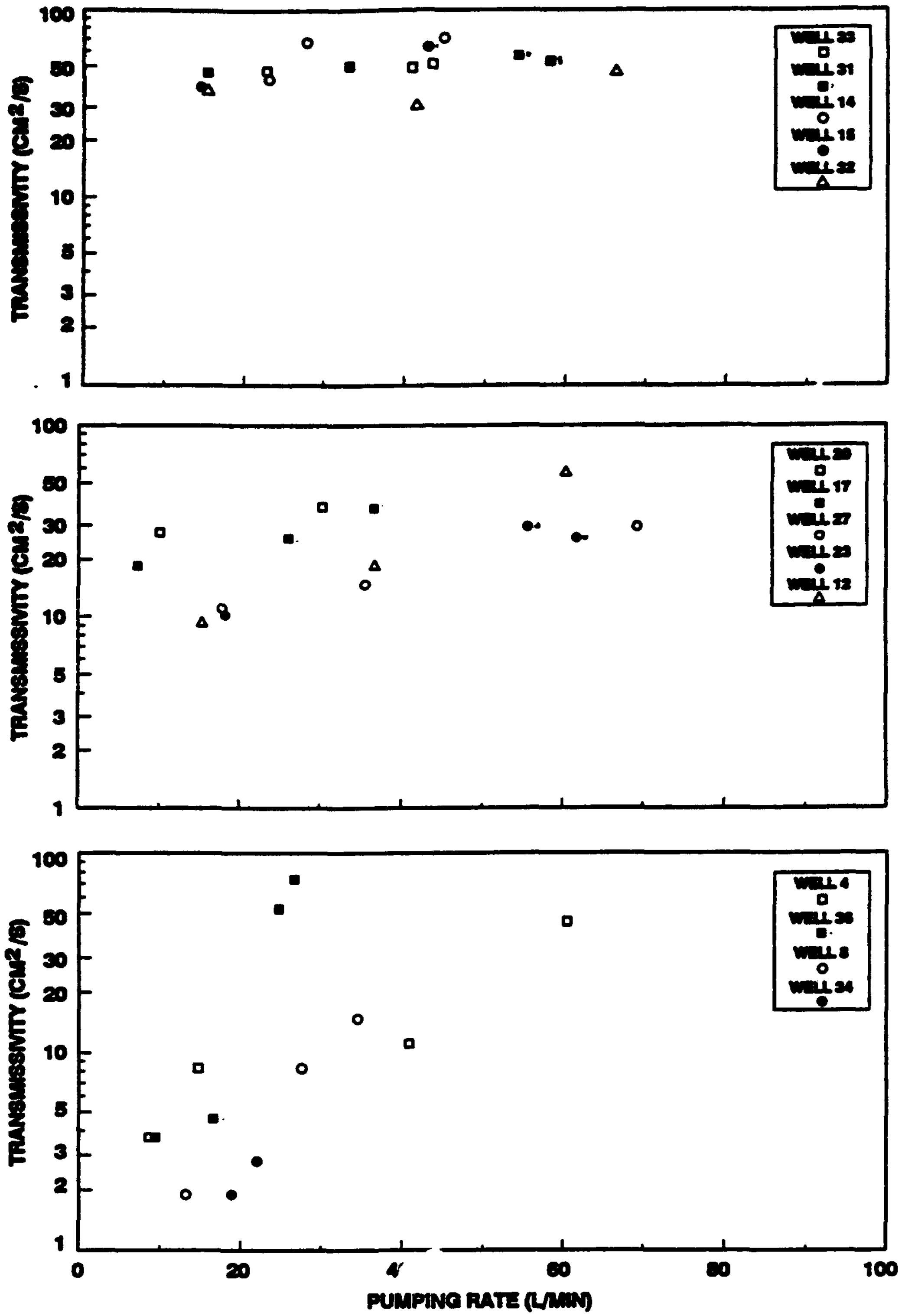

Figure 50. Calculated Transmissivities for Well Locations Where Transmissivity Increased With Increases in the Pumping Rate.

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SECTION VIII

THE TRANSMISSIVITY FIELD DETERMINED FROM AQUIFER TESTS AND FROM SINGLE-WELL TESTS

A. MAPS OF THE TRANSMISSIVITY FIELD

Figures 51 to 56 show the transmissivity fields produced by the large-scale aquifer tests and the single-well tests, which are discussed in Sections V through VII. The figures were generated by the program GCONT (Harper, 1990), which uses a finite-element interpolation scheme. Table 31 lists some important features of the transmissivity fields.

TABLE 31. TRENDS IN THE TRANSMISSIVITY FIELDS DETERMINED BY THE LARGE-SCALE AND THE SINGLE-WELL TESTS

(1) The differences among the large-scale aquifer test results are minimal when compared to the difference between the large-scale aquifer test results and the single-well test results;

(2) The slug test results differ sharply from any of the other results;

(3) The results for the low-rate pumping tests and the high-rate pumping tests show that an increase in the pumping rate by a factor of 3 to 5 can significantly reduce the amount of variability in the transmissivity field;

(4) The overall transmissivity pattern for the injection and the low-rate pumping tests is very similar;

(5) A zone of relatively low transmissivity in the vicinity of Wells 8, 10, and 12 is shown by the results of the short-duration pump tests, the injection tests, and the low-rate pump tests;

(6) A zone of relatively high transmissivity in the vicinity of Wells 37, 28, 2, 3, and 26 is shown by the results of the short-duration pump tests, the injection tests, and the low-rate pump tests; and

(7) The results of the short-duration pump tests appear as if they are a combination of the slug test results and the injection test results.

B. THE DEPOSITIONAL HISTORY AT THE TEST SITE

At several times, aerial photographs have been made of Columbus Air Force Base. A 1956 aerial photograph of the area near the test site

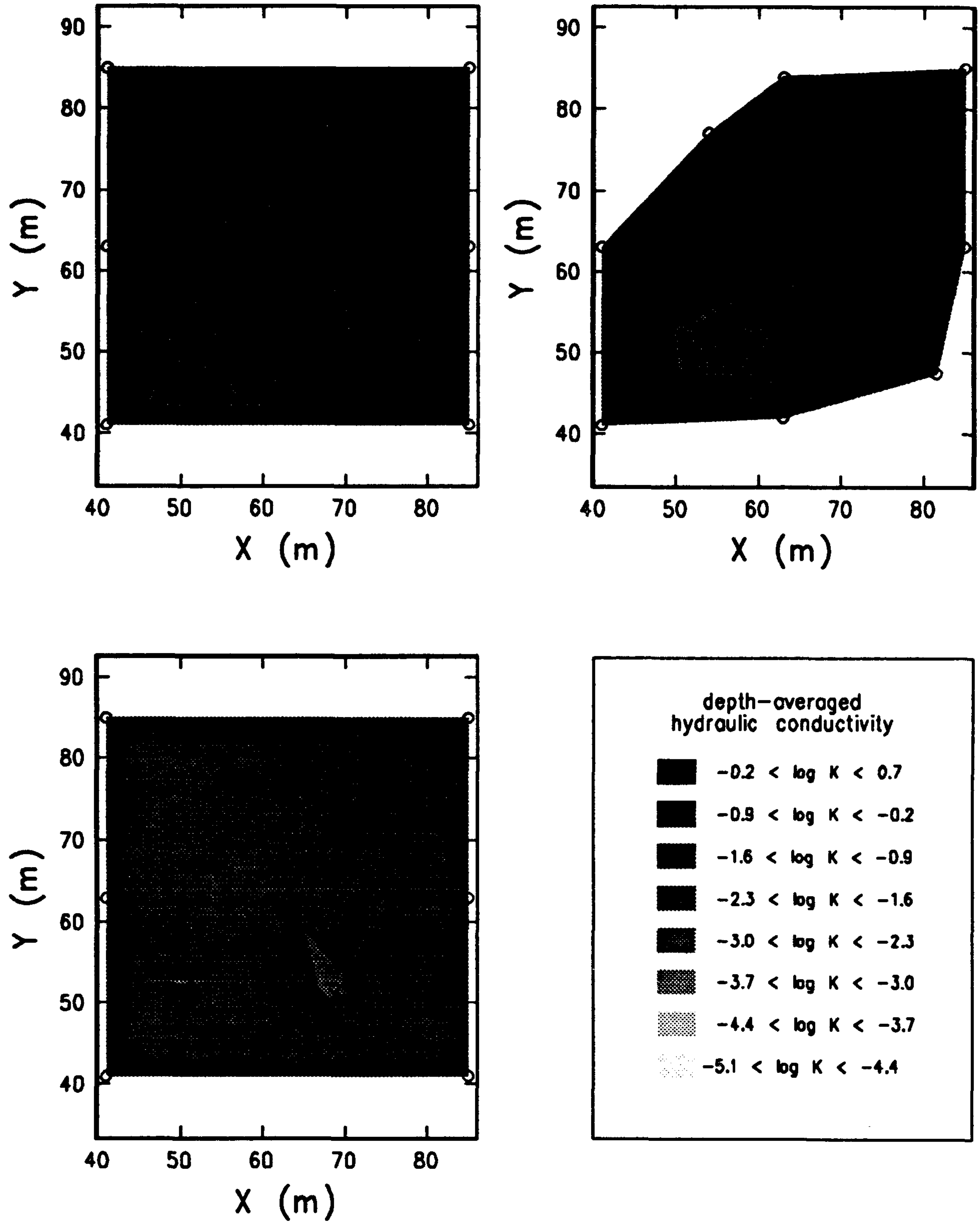

Figure 51. Transmissivity Fields Based on the Large-Scale Aquifer Tests.

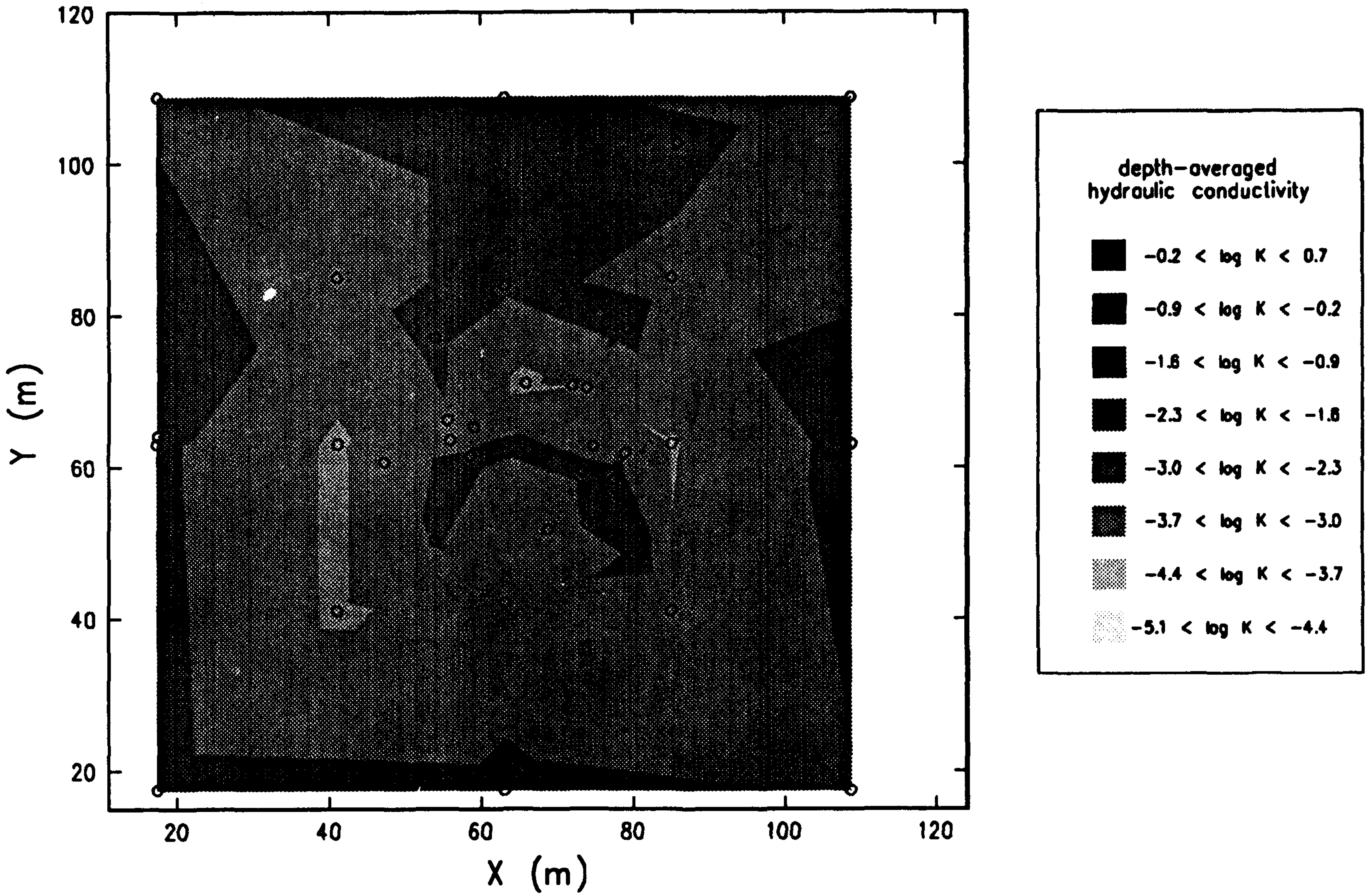

Figure 52. Transmissivity Field Based on the Slug Test Results From the 37 Wells.

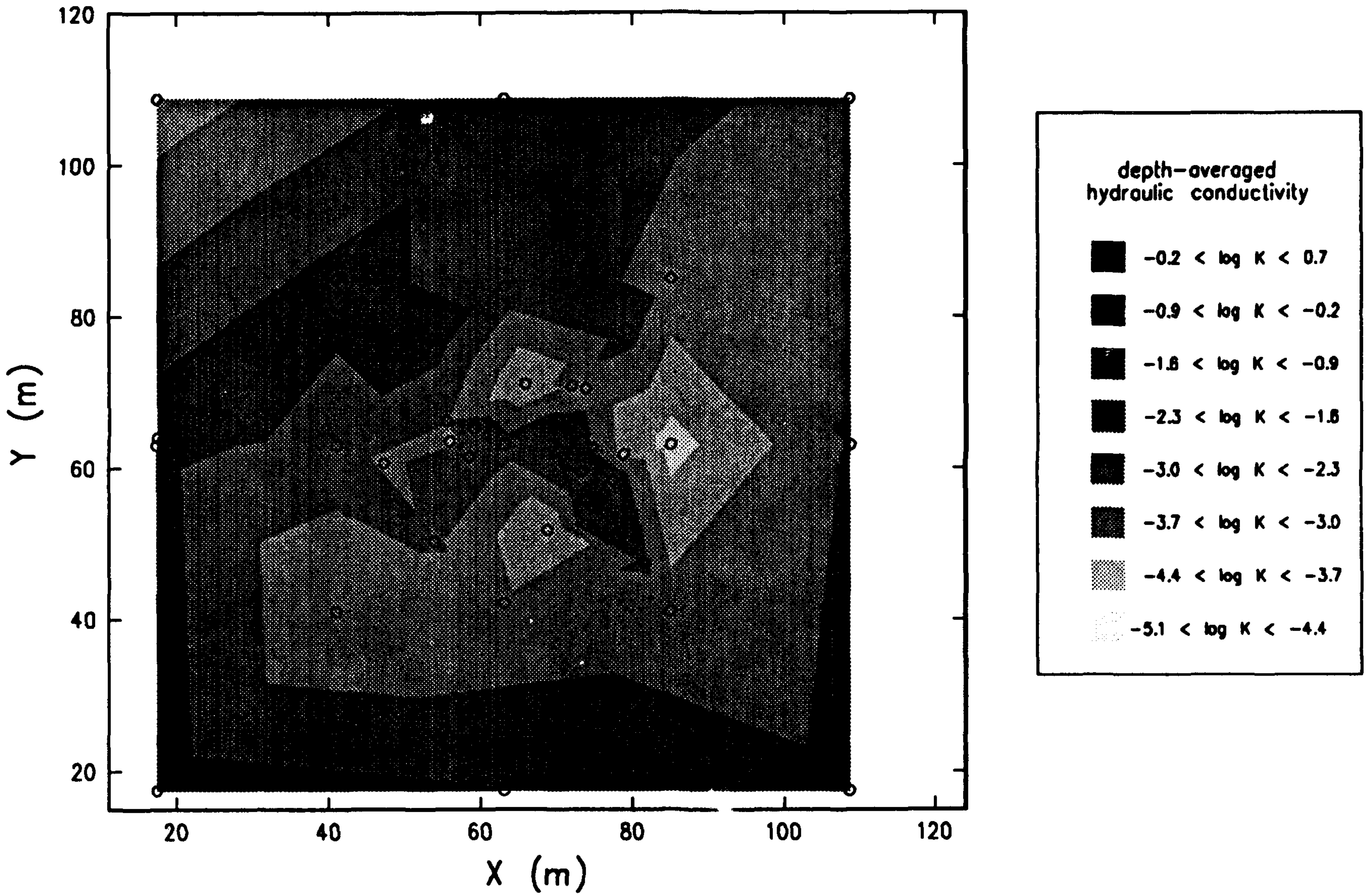

Figure 53. Transmissivity Field Based on the Short-Duration Pump Test Results From the 37 Wells.

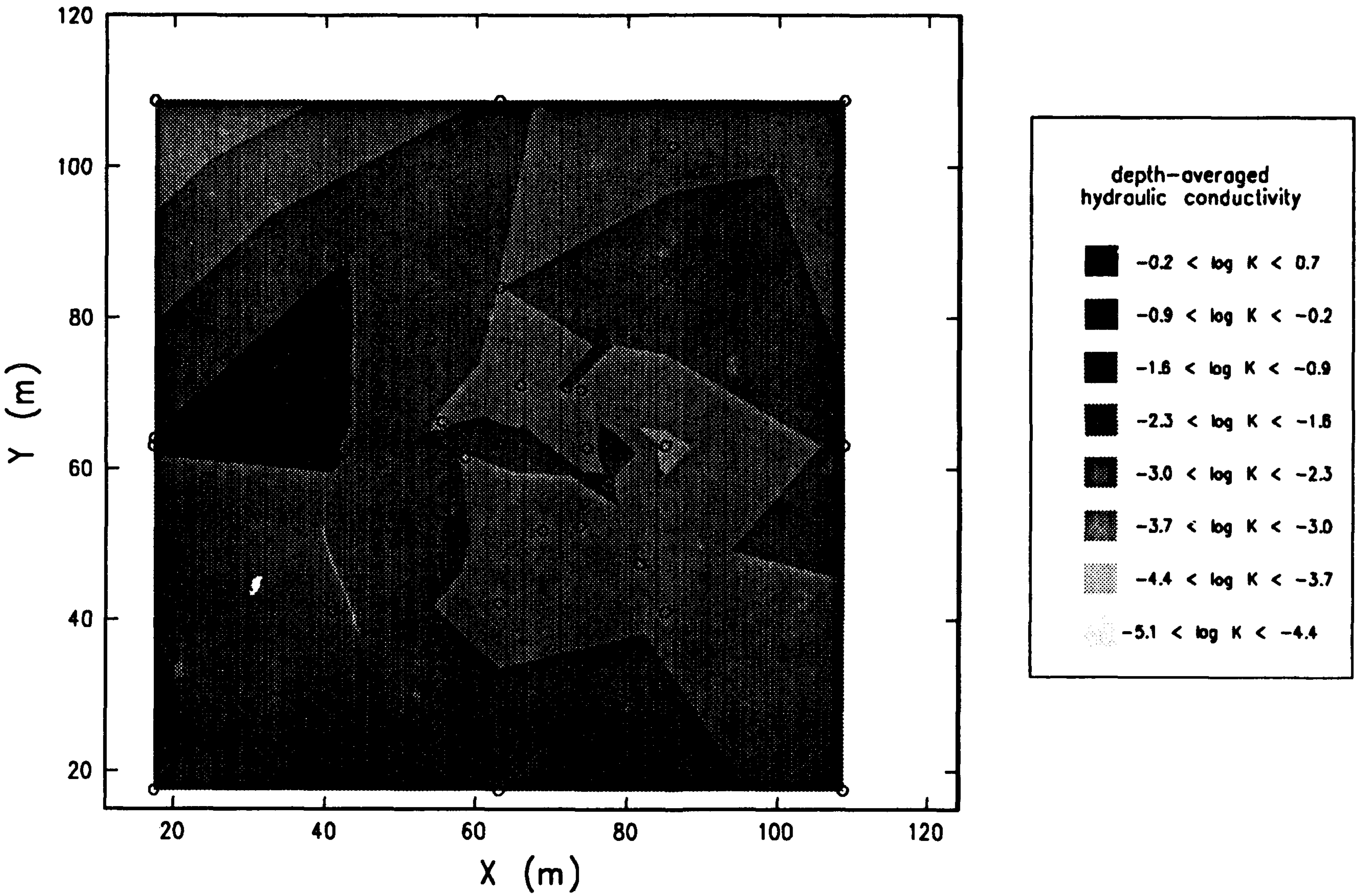

Figure 54. Transmissivity Field Based on the Injection Pump Test Results From the 37 Wells.

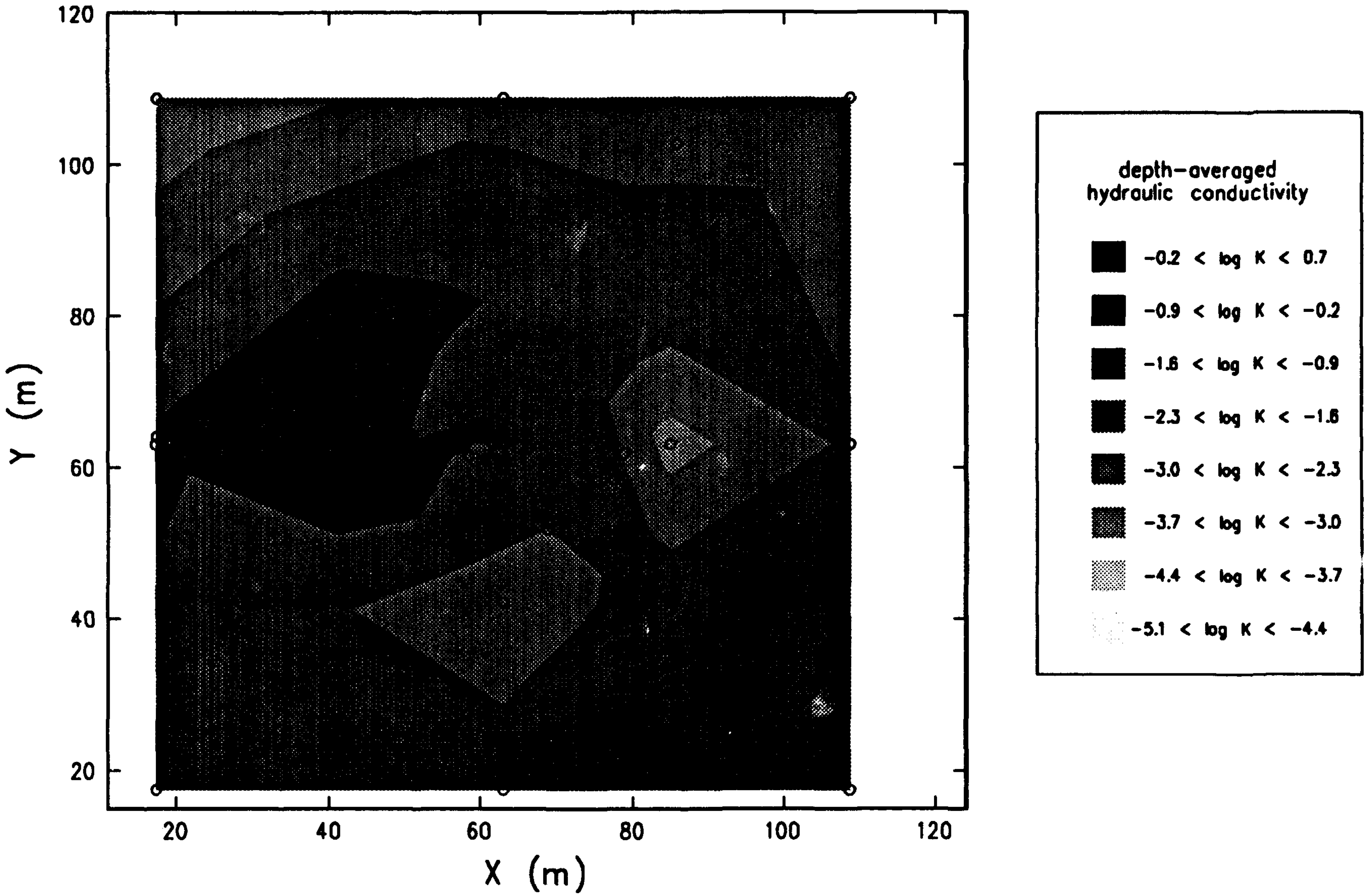

Figure 55. Transmissivity Field Based on the Low-Rate Pumping Test Results From the 37 Wells.

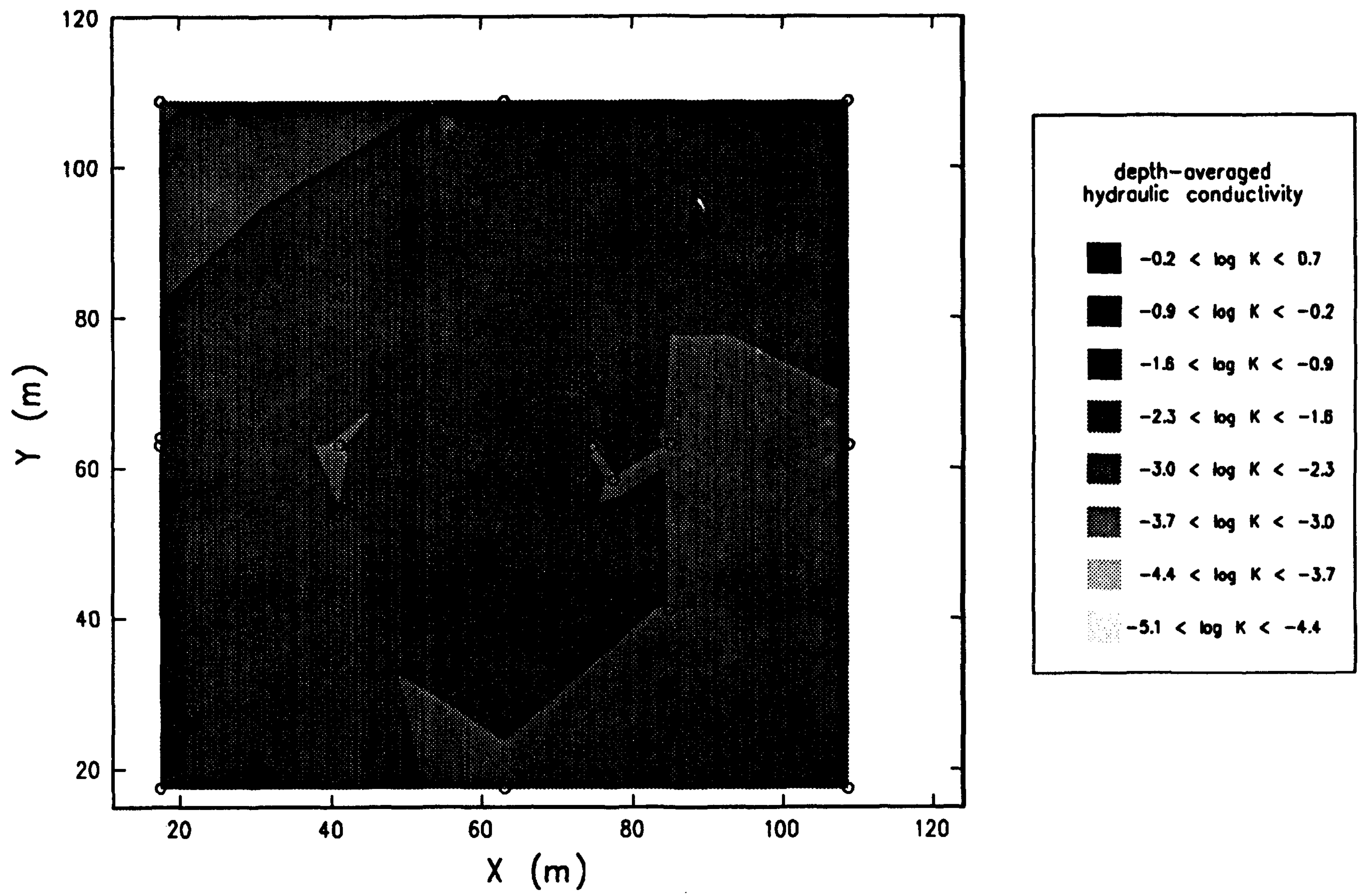

Figure 56. Transmissivity Field Based on the High-Rate Pumping Test Results From the 37 Wells.

shows the remnants of a river meander. Aerial photographs taken several years previously show a recently leveled area that lacks any physiographical indication of a river meander. In 1956, however, differences in the growth patterns of newly developed vegetation silhouetted a former river meander. Photographs taken after 1956 do not show the river meander because of a dense vegetation cover. Figure 55 shows the test site superimposed on the fortuitous 1956 river meander silhouette.

Figure 57 indicates that the 1-hectare test site includes the river channel in the northwestern and northern areas and the point bar in the southeastern locations. In general, the river channel will contain layers of gravel and coarse sands whereas the point bar will contain layers of finer sands and silts. Additional geological information based on soil cores and the outcrops near the test site (Muto, 1986; and Rehfeldt, et al., 1990) indicates that the river meander cut through sediments deposited by a braided river environment. In general, the main channel of a braided river is unstable; bars, and partly cut-off channels appear and disappear. As a result, the deposited materials will consist of bar-shaped lenses of poorly-sorted coarse material (from the high flow periods) and silty material deposited in abandoned channels.

C. THE MOST APPROPRIATE TRANSMISSIVITY FIELD

The depositional environment that formed the aquifer in the test site is very complex. Because of its complexity and importance, the geology of the test site will be discussed in detail in Volume II. For the purpose of this section, a brief and simplified summary is provided concerning the effect that the depositional environment has on the variability in the transmissivity field.

The braided river environment would produce stringers of high and low hydraulic conductivity lenses that finger throughout the aquifer. The meandering river environment would create lenses of high transmissivity within the channel and zones of low transmissivity near the point bar. In both alluvial environments, high flood stages could have produced sheets of high and low permeability sediments. As a result of its

Figure 57. Ox Bow Meander at the CAFB Test Site as Shown in a 1956 Aerial Photograph.

depositional history, the test site could be expected to more closely have the type of transmissivity field indicated by the low-rate pumping tests and the injection tests than any of the other transmissivity fields shown in Figures 51 to 56.

D. INDIRECT MAPPING OF TRANSMISSIVITY ZONES

As previously stated, the trends in the transmissivities calculated at different pumping rates at a well indicates whether the well is adjacent to areas of higher or lower transmissivities. A trend at one well does not provide enough information to locate the areas of different transmissivities. However, if they are mapped and examined collectively, the trends at a series of wells can provide the information required to qualitatively help map the large-scale trends in the transmissivity field.

Figure 58 was created from the information in Figures 49 and 50. Figure 58 maps a high conductivity zone in the vicinity of Wells 2, 3, 18, 26, 6, and 9. The location of this high conductivity zone matches very closely with the location of the former river channel. The results in Figure 58 indicate the following about the trends shown in Figures 49 and 50: (1) the trends are real and not an artifact of the method of data collection; and (2) the trends can be used to help determine an aquifer's hydraulic structure.

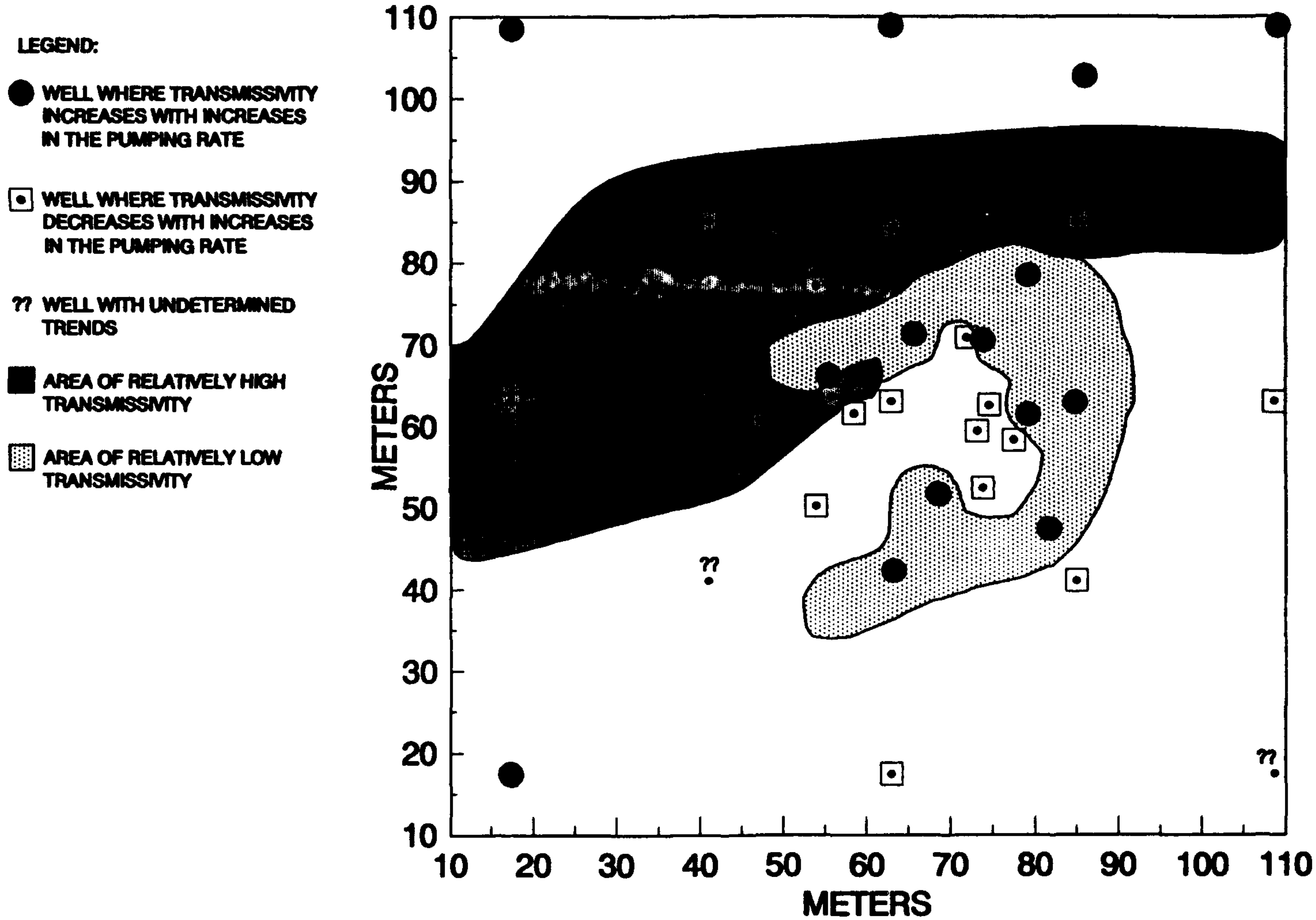

Figure 58. Areas of High Transmissivity and Low Transmissivity Determined From the Effects That the Pumping Rate Has on the Calculated Transmissivity at Each Well.

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SECTION IX

SUMMARY

A. TEST SITE AND WELL NETWORK

The 1 hectare test site is located at Columbus AFB, Mississippi, and is approximately 6 km east of the Tombigbee River and 2.5 km south of the Buttahatchee River. The 11-meter thick terrace aquifer consists of a mixture of gravel, sand, and clay lenses and is underlain by the Cretaceous Age Eutaw Formation, which consists primarily of marine clay, silt, and sand. Compared to unconsolidated aquifers found in coastal, glacial, and lacustrine setting, the alluvial aquifer at Columbus AFB is very heterogeneous.

A network of 37 wells was designed to meet multiple objectives which include small- and large-scale pump and tracer tests. Given the constraints of these multiple objectives, the well network was optimized with regard to geostatistical analyses by using the ideas presented by Warrick, et al. (1987), and by Olea (1975), on the optimal location of data for semivariogram analyses and kriging analyses, respectively. Geostatistical analysis was selected a priori as the best method for interpreting three-dimensional hydraulic conductivity data set. An evaluation of the potential for this type of analyses is provided in Volume II.

Four well installation methods were used to create the well network. The four well installation methods were the cable tool, rotary wash, hollow-stem auger, and air percussion. The most cost-effective method was the hollow-stem auger. This method also proved to be the most effective method for collecting soil samples. From the aspect of costs and soil sampling, the best and worst overall well installation methods were the hollow-stem auger and the air percussion methods, respectively.

B. WELL EQUATIONS FOR HOMOGENEOUS AQUIFERS

All of pump test analyses in Volume I and II are based on a form of the Theis solution (1935) which solves for radial groundwater flow to a

well in a confined aquifer. The basic assumptions and applications of the Theis solution are discussed along with several important modifications and/or approximation to the Theis solution. The Cooper-Jacob equation (1946) has the advantage of being much easier than the Theis solution to apply but has the disadvantage of being valid only at times large enough to make the dimensionless time parameter, u, less than 0.01.

Both the Theis and the Cooper-Jacob equations require values for storage coefficient and the transmissivity. The Cooper-Jacob straight-line analysis (1946), a form of the Cooper-Jacob equation, can be used to determine the transmissivity from a time-drawdown curve independent of the storage coefficient. The report derives both the Cooper-Jacob equation and the Cooper-Jacob straight-line analysis from the Theis solution. In addition, the report discusses and derives the Thiem equation from the Cooper-Jacob equation. The Thiem equation predicts the drawdown difference at two wells located at different radial distances from a pumping well.

By comparing analytical and numerical results, the report shows that the well equations for a confined aquifer are applicable for an unconfined aquifer when the drawdown is less than 20 percent of the aquifer's total saturated thickness. When the drawdown values are greater than 20 percent of the total thickness of the saturated aquifer, the report shows that the confined equations are valid after the Jacob correction factor has been applied to the drawdown values for most practical groundwater problems.

C. CONSIDERATIONS WHEN USING WELL EQUATIONS AT CAFB

The usefulness of the hydraulic parameters predicted by pump test analyses is closely related to whether or not the assumptions made in the derivation of the well equations are valid. Three important phenomena that violate the assumptions of the equations are skin effects, well headlosses, and hydraulic conductivity variations. The report defines and discusses each of the terms. An important phenomena, at least for the Columbus test site, is skin effects. Skin effects represent the

disturbed zone about a well created during the well installation. A negative skin effect means that the hydraulic conductivity of the natural aquifer material near the well has been reduced. Negative skin effects can be caused by the smearing of clay particles, the compaction of sediments during the advancement of the drill casing, and/or the intrusion of fines into coarse sediments because of improper well development.

D. TRANSMISSIVITIES AND STORAGE COEFFICIENTS FROM LARGE- AND SMALL-SCALE AQUIFER TESTS

Traditionally, aquifer tests have been the standard method to determine the average hydraulic properties of an aquifer. The report discusses the development of a computer program that automatically determines which set of values for the transmissivity and the storage coefficient produce a time-drawdown curve that best matches the experimental data set. The computer code was used to demonstrate the important effects that the aquifer test design can have on the uncertainties associated with data analyses. Based on the results of the computer program, three large-scale and several small-scale aquifer tests were designed.

The report provides a detailed description of the design and the procedures used to conduct the aquifer tests. Each large-scale aquifer test lasted about 6 days. Well monitoring included manual water table measurements in all 37 wells with an electric tape and automatic water table measurements in 9 to 11 wells, at a given time, with pressure transducers. Aquifer Test 1 centered on pumping Well 5 (the center well) at a constant rate of about 68 L/min. Aquifer Test 2 centered on pumping Well 5 at regulated cyclic intervals that produced an average pumping rate of about 68 L/min. Aquifer Test 3 centered on pumping Well 5 a constant rate of about 113 L/min. The small-scale pumping tests centered on pumping a series of wells at rates between 34 and 81 L/min, and monitoring the water table in wells 4 to 7 meters away, from 1 to 2 hours.

For Aquifer Tests 1 and 3, the report shows a potentiometric map based on the water tables in all 37 wells at four different times during

each test. The potentiometric map shows an asymmetric cone-of-depression and temporal variations in the asymmetric patterns. The report also compares the observed and the matched drawdown curves at the 9 to 11 locations of the pressure transducers for Aquifer Tests 1 and 3. For Aquifer Test 2 the report compares the observed and the matched drawdown curves at 36 well locations. Note that during Aquifer Test 2 the transducers were moved periodically so that pressure transducers were located in almost all the wells. For the small-scale pump tests only the hydraulic parameters calculated for the computer program are presented.

For each of the large-scale aquifer tests, transmissivity values were calculated at almost all of the 27 interior wells. The average transmissivity for the aquifer was estimated between 30 and 40 cm^2/s. For Aquifer Test 2, a storage coefficient was calculated at 24 of the 27 interior wells. The average storage coefficient for the aquifer was estimated at about 0.03. An analysis of the potentiometric maps and the trends in the transmissivity indicates that the aquifer materials in the western region have a higher diffusivity than the aquifer materials in the eastern region of the well network.

E. ANALYSIS OF THE THEIS-BASED TRANSMISSIVITIES AND STORAGE COEFFICIENTS

An analyses of the calculated transmissivity and the storage coefficient values show that the values ranged between 10 and 200 cm^2/s and 0.1 and 0.00001, respectively. Given a saturated aquifer thickness of about 7 meters, the values of transmissivity are within the range expected for a sand and gravel aquifer. However, the values for storage coefficients were unexpectedly low. Typically, unconfined aquifers have storage coefficients in the range between 0.3 and 0.01 and confined aquifers have storage coefficients in the range between 0.005 and 0.00005 (Freeze and Cherry, 1976).

The average storage coefficient value of 0.03, which is based on a type-curve analyses of the time-drawdown curves from the aquifer tests, is compared to an average storage coefficient calculated from a volumetric analysis of the cone-of-depressions from the aquifer tests and an estimate of the "true" specific yield from laboratory drainage

experiments. The comparison is very similar to Neuman's (1988) analysis of an aquifer test conducted in a glacial sand aquifer in Canada for which the well type-curve analysis produced a storage coefficient of 0.07. The pump test data from the test site and from the Canadian test site shows the storage coefficient for an unconfined aquifer can be at least 500 percent less than the specific yield calculated from laboratory drainage experiments. This difference occurs because the drainage from the unsaturated zone occurs at a much slower rate than the groundwater level fluctuations due to pumpage. The analysis concludes that in many instances the storage coefficient calculated from an aquifer test are, and should be, significantly less than the "true" specific yield of the aquifer material.

The test results show that the hydraulic properties calculated at observation well locations are affected by the design of the aquifer tests. The test results show differences, one and one to three orders of magnitude change, in the calculated transmissivity and storage coefficient values, respectively, at observation well locations. Important aquifer design parameters include the distance and the orientation between the pumping and the observation wells, the pumping rate, and the duration of the test.

The test results show that the calculated transmissivity and the storage coefficient values decrease and increase, respectively, as the duration of a pump test increases. These trends are attributed to how an aquifer responds to stress caused by pumping. When an aquifer is stressed, the initial pressure response is first transmitted into and through the zones of high diffusivity. Initially, hydraulic pressure in the well will more closely represent the pressure in the zones of high diffusivities rather than an average pressure in the aquifer. Consequently, an analysis of well data, at early times, will lead to estimates of transmissivities and storage coefficients more representative of the zones of high diffusivity rather than of the total thickness of the aquifer. Because cross flow causes the pressure gradients between the zones of high and low diffusivity to dissipate over time, the hydraulic pressure in the well, will at late times, more closely represent the pressure in the total aquifer than in the zones of

high diffusivity. Consequently, an analysis of well data, at late times, will lead to estimates of transmissivity and storage coefficients more representative of all aquifer material than materials of high diffusivity.

The aquifer test results show a correlation between the distance between the pumping and the observation wells and the value of the storage coefficient. The observed trends indicated that the storage coefficients ranged between 10^{-6} to 10^{-2} for distances between 0 and 10 meters, 10^{-4} to 10^{-2} for distances between 10 and 20 meters, and 10^{-2} to 10^{-1} for distances greater than 20 meters. The report provides a plausible explanation for these trends which centers on having discrete highly permeable lenses scattered throughout the aquifer (an occurrence shown in Volume II). In general, the lower values of storage coefficients occur when a highly transmissive, thin lens (or a series of lenses) intersect both the pumping and the observation well. Higher values of storage coefficients occur when the aquifer material between the pumping and the observation well is more homogeneous and does not have continuous lenses that intersect both wells. The data indicates that the correlation between storage coefficients and distance is likely to be typical of heterogeneous aquifers. In short, for heterogeneous aquifers, the likelihood of calculating low storage coefficient values decreases with increasing distance between the pumping and the observation wells, because at greater distances there is less likelihood that a thin lens of high conductivity intersects the two wells.

F. TRANSMISSIVITIES FROM SINGLE-WELL TESTS

At each well, a series of single-well pump tests were conducted to determine the aquifer's transmissivity. The pump tests included slug tests, short-duration (2-minutes) pump tests, low-rate (15 L/min) pumping tests, moderate-rate (20-30 L/min) injection and/or pumping tests, and high rate (60 L/min) pumping test. At 27 of the 37 well locations, the transmissivities from the single-well tests ranged over an order of magnitude. The test results show that the design of a single-well test affects the transmissivity calculated at the pumped well. Important design features are the pumping rate and the duration of a pump test.

The test results show that the single-well test with the smallest radius of influence (i.e., the slug test and the short duration pump test) have mean transmissivity values considerably less than the mean transmissivity values for the aquifer tests. The single-well test with the largest radius of influence (i.e., the high-rate pumping test and the injection tests) have mean transmissivity values that closely match the mean transmissivity values for the aquifer tests.

The low transmissivity values from the slug tests and short-duration pump tests indicate that negative skin effects are at the wells. The analyses of the pumping tests also indicate that negative skin effects exists at the wells. Skin effects are supported by the difference in transmissivity values calculated from the Cooper-Jacob equation (no skin effects assumed) and the Cooper-Jacob straight-line analysis (skin effects accounted for). The analysis of the pumping tests showed that, on the average, Cooper-Jacob straight-line analysis gave transmissivity values about an order of magnitude higher than the Cooper-Jacob equation.

The test results show that at about half the wells, the calculated transmissivity is very sensitive to the pumping rate. The sensitivity of the calculated transmissivity to the pumping rate occurs because the hydraulic properties of the aquifer change with distance from the well. In a heterogeneous aquifers low pumping rates will produce transmissivity values more reflective of the local aquifer material, whereas high pumping rates will produce transmissivity values that represents a weighted average of the local and the regional aquifer properties.

At some of the wells (2, 18, 19, 16, 28, 37, and 26), the calculated transmissivity values increased over an order of magnitude with increases in the pumping rate. At other wells (4, 36, 8, and 34) the transmissivity values decreased over an order of magnitude. At about half the wells, the increase in the pumping rate changed the calculated transmissivities by less than a factor of four. The trends in the data indicate a large zone of highly transmissivity material in the west and the north and a large zone of moderate transmissivity material in the east. Overall, the tests results show that the pumping rates can have a large effect on the calculated transmissivities for single-well tests.

G. THE TRANSMISSIVITY FIELD DETERMINED FROM THE AQUIFER TESTS AND FROM THE SINGLE-WELL TESTS

The report compares the different transmissivity fields produced by the different aquifer and the single-well pump tests. The large-scale aquifer tests produce transmissivity fields that have little variability. The low-rate pumping and the moderate-rate injection single-well tests produce transmissivity fields with considerably more variability. A low transmissivity region is in the east (Wells 8, 10, and 12) and a high transmissivity region is in the west (Wells 37, 28, 2, 3, and 26). The high-rate pumping single-well tests produce a transmissivity field that resembles a mix between the transmissivity fields produced by the large-scale aquifer test results and of the low-rate pumping single-well test results. The slug tests produce a transmissivity field that resembles none of the transmissivity fields for the single-well or pump tests. The short-duration single-well pump tests produce a transmissivity field that is in between the transmissivity fields produced by slug tests and low-rate single-well pumping tests.

One can see, that based on the wide range of results for pump tests, more than a comparison of the different pump test data are required to evaluate the "correctness" and/or the "incorrectness" of the different transmissivity field as related to the type of characterization needed for designing bioreclamation systems. The ideal data set for ground-truthing the "correctness" of each transmissivity field are results of a large-scale tracer test. This type of information, however, will not be discussed until Volume II. For the interim, two sources of information were provided to support the selection of the single-well pumping tests as the best method for mapping the transmissivity field.

The first source of information was a 1956 aerial photograph of the site that shows a former river channel in the northwestern and the northern regions and a presumed point bar in the southeastern region of the well network. The second source of information was a qualitative map of the high and low regions of transmissivity based on the trends between the calculated transmissivity values and the pumping rate. Both of these sources of information are in best agreement with the trends shown in the

transmissivity fields for the low-rate pumping and moderate-rate injecting single-well pump tests.

H. OVERALL ASSESSMENT

The different transmissivity fields from the different pump tests show that the estimated transmissivity field is very dependent on the type of pump test. Moreover, the report contains numerous graphs and tables that show that for each particular type of pump tests, several different transmissivity fields could be created by varying the design of the particular type of pump test. As such, one can see that considerable care must be exercised in designing a site characterization program for delineating the transmissivity field. One needs to know how to select and design a pump test for measuring what is being sought. What is being sought in most site characterization activities for bioreclamation systems is the transmissivity field at the scale of a few meters. Based on the previous discussion of aquifer hydraulics and the test results, the best site characterization method for transmissivity is the low-rate single-well pumping tests.

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SECTION X

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APPENDIX A

CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 2

TABLE A-1. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 2 FOR PULSES 1 TO 6

	Pulses		Transmissivity			Storage Coefficient		
Well	From	To	Value	10%	20%	Value	10%	20%
2	1	6	42.46	NC	*/1.26	.053703	*/1.00	*/1.55
2	1	3	39.63	NC	*/1.35	.063096	NC	*/1.58
2	4	6	46.56	NC	*/1.20	.041687	NC	*/1.51
4	1	6	29.38	NC	*/1.29	.040738	NC	*/1.78
4	1	3	28.06	NC	*/1.32	.050119	NC	*/1.55
4	4	6	31.48	*/1.05	*/1.29	.028840	*/1.10	*/2.09
6	1	6	32.21	NC	*/1.26	.020417	NC	*/1.95
6	1	3	33.73	NC	*/1.29	.023988	NC	*/1.74
6	4	6	33.73	*/1.07	*/1.29	.013804	*/1.20	*/2.34
8	1	6	20.80	NC	NC	.014125	NC	NC
8	1	3	22.29	NC	NC	.007079	NC	NC
8	4	6	15.42	NC	NC	.040738	NC	NC
14	1	6	27.42	*/1.07	*/1.26	.005248	*/1.41	*/3.02
14	1	3	26.79	*/1.07	*/1.26	.005623	*/1.38	*/2.69
14	4	6	27.42	*/1.10	*/1.26	.004571	*/1.55	*/3.47
15	1	6	32.21	NC	*/1.26	.012303	NC	*/2.40
15	1	3	35.32	NC	*/1.23	.011220	NC	*/2.14
15	4	6	31.48	*/1.10	*/1.26	.010965	*/1.45	*/2.88
17	1	6	26.79	NC	*/1.23	.008128	NC	*/2.45
17	1	3	27.42	NC	*/1.23	.009772	NC	*/2.04
17	4	6	26.79	*/1.10	*/1.26	.006026	*/1.48	*/3.09
19	1	6	25.00	*/1.10	*/1.23	.002570	*/1.62	*/3.63
19	1	3	24.44	*/1.10	*/1.23	.002818	*/1.70	*/3.47
19	4	6	25.59	*/1.07	*/1.23	.002188	*/1.62	*/3.98
20	1	6	26.18	*/1.10	*/1.26	.006026	*/1.58	*/3.24
20	1	3	27.42	*/1.10	*/1.26	.005888	*/1.51	*/2.88
20	4	6	26.18	*/1.10	*/1.26	.005495	*/1.74	*/3.63
25	1	6	29.38	NC	*/1.26	.093325	NC	*/1.74
25	1	3	30.76	NC	*/1.26	.100000	NC	*/1.55
25	4	6	31.48	NC	*/1.29	.064565	NC	*/2.09
26	1	6	29.38	*/1.05	*/1.26	.005754	*/1.17	*/2.45
26	1	3	30.06	*/1.07	*/1.26	.006310	*/1.32	*/2.34
26	4	6	30.06	*/1.05	*/1.26	.004571	*/1.23	*/2.69
30	1	6	12.53	NC	*/1.17	.014791	NC	*/1.48
30	1	3	11.70	NC	*/1.17	.013804	NC	*/1.41
30	4	6	12.25	NC	*/1.20	.020417	NC	*/1.70

NC = not calculated
*/ = multiplied or divided by

TABLE A-2. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 2 FOR PULSES 8 TO 13

	Pulses		Transmissivity			Storage Coefficient		
Well	From	To	Value	10%	20%	Value	10%	20%
1	8	13	70.47	NC	*/1.26	.017378	NC	*/2.29
1	8	10	58.62	*/1.10	*/1.29	.021380	*/1.38	*/2.45
1	11	13	82.80	*/1.05	*/1.29	.017378	*/1.26	*/2.88
9	8	13	41.50	*/1.07	*/1.29	.028184	*/1.23	*/2.24
9	8	10	37.85	*/1.12	*/1.29	.028184	*/1.35	*/2.19
9	11	13	42.46	*/1.12	*/1.29	.033884	*/1.45	*/2.34
10	8	13	57.28	NC	*/1.20	.038019	NC	*/2.14
10	8	10	44.46	*/1.07	*/1.26	.070795	*/1.23	*/2.51
10	11	13	67.30	NC	*/1.23	.031623	NC	*/2.69
11	8	13	33.73	*/1.10	*/1.26	.019953	*/1.45	*/3.02
11	8	10	32.21	*/1.10	*/1.26	.021380	*/1.41	*/2.82
11	11	13	35.32	*/1.10	*/1.26	.019953	*/1.51	*/3.24
12	8	13	21.28	NC	*/1.12	.026915	NC	*/1.51
12	8	10	19.86	NC	*/1.17	.029512	NC	*/1.66
12	11	13	22.29	NC	*/1.12	.028840	NC	*/1.51
13	8	13	26.79	*/1.10	*/1.23	.001445	*/2.29	*/6.46
13	8	10	25.59	*/1.10	*/1.23	.001778	*/2.19	*/5.89
13	11	13	28.06	*/1.10	*/1.23	.001288	*/2.51	*/7.41
13	8	13	26.79	*/1.10	*/1.23	.001445	*/2.29	*/6.46
13	8	10	25.59	*/1.10	*/1.23	.001778	*/2.19	*/5.89
13	11	13	28.06	*/1.10	*/1.23	.001288	*/2.51	*/7.41
16	8	13	31.48	*/1.10	*/1.23	.000457	*/2.63	*/8.51
16	8	10	29.38	*/1.10	*/1.23	.000603	*/2.57	*/7.76
16	11	13	32.21	*/1.10	*/1.23	.000380	*/2.82	*/9.55
18	8	13	47.64	*/1.07	*/1.26	.017378	*/1.29	*/2.88
18	8	10	43.45	*/1.10	*/1.26	.019953	*/1.38	*/2.75
18	11	13	52.24	*/1.10	*/1.26	.016596	*/1.55	*/3.31
21	8	13	32.96	*/1.10	*/1.29	.051286	*/1.38	*/2.51
21	8	10	30.06	*/1.12	*/1.29	.058884	*/1.38	*/2.34
21	11	13	35.32	*/1.12	*/1.29	.050119	*/1.55	*/2.75
24	8	13	33.73	*/1.10	*/1.29	.045709	*/1.38	*/2.57
24	8	10	32.21	*/1.10	*/1.29	.045709	*/1.38	*/2.45
24	11	13	34.52	*/1.12	*/1.29	.051286	*/1.51	*/2.69
31	8	13	39.63	*/1.05	*/1.29	.042658	*/1.15	*/2.29
31	8	10	35.32	*/1.12	*/1.29	.045709	*/1.38	*/2.24
31	11	13	42.46	*/1.10	*/1.29	.044668	*/1.45	*/2.51
32	8	13	37.85	*/1.07	*/1.29	.050119	*/1.26	*/2.24
32	8	10	36.14	*/1.10	*/1.29	.048978	*/1.32	*/2.14
32	11	13	39.63	*/1.10	*/1.29	.054954	*/1.38	*/2.34

NC = not calculated
*/ = multiplied or divided by

TABLE A-3. CALCULATED STORAGE COEFFICIENTS AND TRANSMISSIVITIES FOR AQUIFER TEST 2 FOR PULSES 15 TO 20

	Pulses		Transmissivity			Storage Coefficient		
Well	From	To	Value	10%	20%	Value	10%	20%
3	15	20	80.91	*/1.10	*/1.29	.034674	*/1.41	*/2.75
3	15	17	73.79	*/1.12	*/1.29	.034674	*/1.58	*/2.75
3	18	20	88.72	*/1.12	*/1.29	.036308	*/1.70	*/2.95
7	15	20	61.38	*/1.10	*/1.29	.021878	*/1.45	*/2.88
7	15	17	52.24	*/1.12	*/1.29	.025704	*/1.55	*/2.69
7	18	20	53.46	*/1.12	*/1.29	.036308	*/1.55	*/2.63
10	15	20	44.46	NC	NC	.077625	NC	NC
10	15	17	62.81	NC	*/1.26	.058884	NC	*/2.69
10	18	20	37.85	*/1.10	*/1.26	.064565	*/1.55	*/3.09
11	15	20	40.55	*/1.10	*/1.26	.012303	*/1.55	*/3.72
11	15	17	37.85	*/1.10	*/1.26	.015136	*/1.66	*/3.72
11	18	20	42.46	*/1.10	*/1.26	.012023	*/1.58	*/3.98
12	15	20	51.05	NC	NC	.008318	NC	NC
12	15	17	44.46	NC	NC	.014454	NC	NC
12	18	20	57.28	NC	NC	.004169	NC	NC
13	15	20	33.73	*/1.10	*/1.23	.000550	*/2.45	*/8.71
13	15	17	31.48	*/1.10	*/1.23	.000955	*/2.29	*/7.59
13	18	20	34.52	*/1.10	*/1.23	.000437	*/2.82	*/10.1
16	15	20	39.63	*/1.10	*/1.23	.000102	*/2.57	*/10.3
16	15	17	37.85	*/1.07	*/1.23	.000135	*/2.45	*/10.5
16	18	20	42.46	*/1.10	*/1.23	.000054	*/2.88	*/10.5
18	15	20	67.30	*/1.05	*/1.26	.009333	*/1.26	*/3.55
18	15	17	58.62	*/1.12	*/1.26	.011749	*/1.74	*/3.89
18	18	20	72.11	*/1.07	*/1.26	.008710	*/1.38	*/3.80
21	15	20	67.30	NC	NC	.031623	NC	NC
21	15	17	52.24	*/1.12	*/1.26	.035481	*/1.62	*/3.16
21	18	20	82.80	NC	*/1.23	.034674	NC	*/3.02
24	15	20	37.85	*/1.12	*/1.26	.038905	*/1.62	*/3.09
24	15	17	36.98	*/1.12	*/1.26	.039811	*/1.66	*/3.02
24	18	20	38.73	*/1.12	*/1.26	.040738	*/1.66	*/3.16
31	15	20	53.46	*/1.12	*/1.29	.037154	*/1.62	*/2.88
31	15	17	52.24	*/1.12	*/1.29	.038019	*/1.62	*/2.88
31	18	20	54.70	*/1.12	*/1.29	.037154	*/1.66	*/2.95
32	15	20	47.64	*/1.12	*/1.29	.038019	*/1.55	*/2.69
32	15	17	44.46	*/1.12	*/1.29	.039811	*/1.51	*/2.63
32	18	20	47.64	*/1.12	*/1.29	.044668	*/1.58	*/2.69

NC = not calculated
*/ = multiplied or divided by